HIGH TEMPERATURE SENSORS AND ELECTRONICS FOR VENUS MISSIONS

Presented by:

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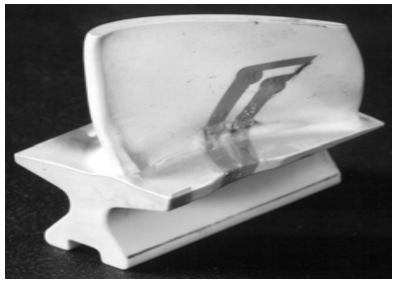
OUTLINE

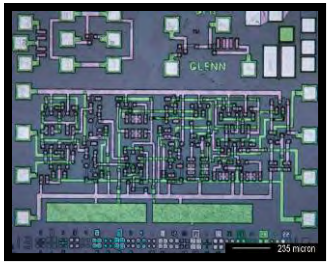
- INTRODUCTION
- AEROSPACE APPLICATIONS
- SiC ELECTRONICS AND PACKAGING DEVELOPMENT
  - HISTORY OF ELECTRONICS DEVELOPMENT
  - RECENT RESULTS
  - ATOMICALLY FLAT SiC
- SENSOR DEVELOPMENT
  - PRESSURE SENSORS
  - HI-g ACCELEROMETER
  - THIN FILM SENSORS
  - HIGH TEMPERATURE ELECTRONIC NOSE
- SUMMARY AND FUTURE PLANS

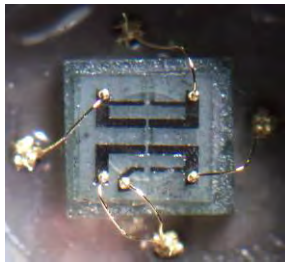
Instrumentation & Controls Division

Sensors & Electronics

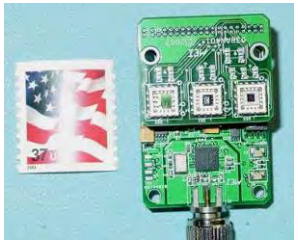


High Temperature
(>1000 °C)
Thin Film Sensors

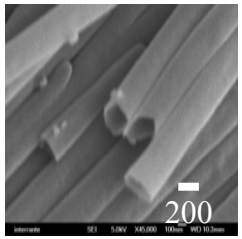




High Temperature (600 °C)
SiC Electronics & Sensors

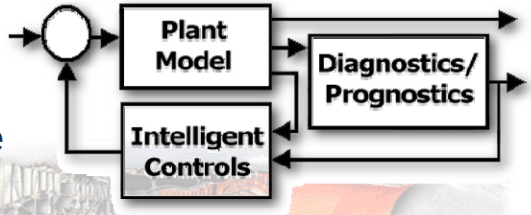


Chemical
Sensors

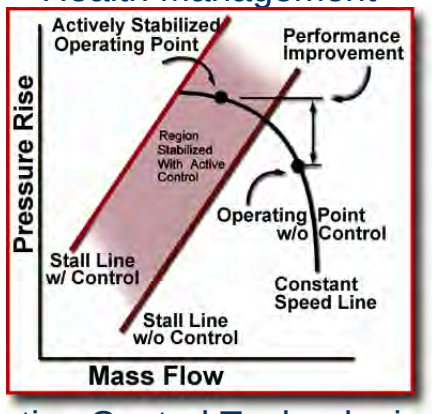


SiC Nanotubes

Controls & Health Management



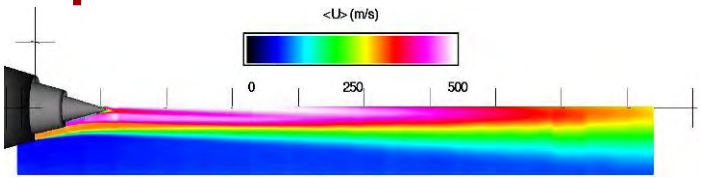
Intelligent Control &
Health Management



Active Control Technologies

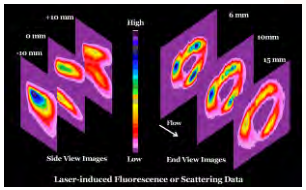
INTELLIGENT AEROSPACE SYSTEMS

Optical Instrumentation & NDE

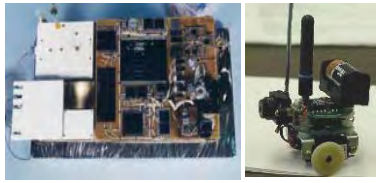


Facility Instrumentation

Combustion Diagnostics

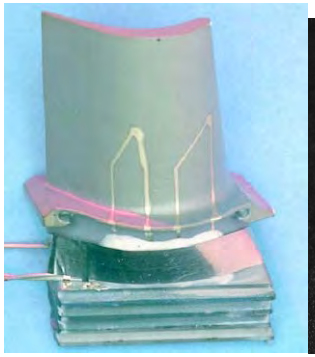


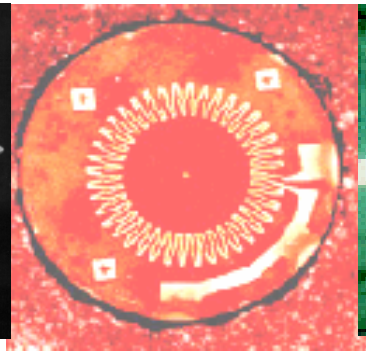
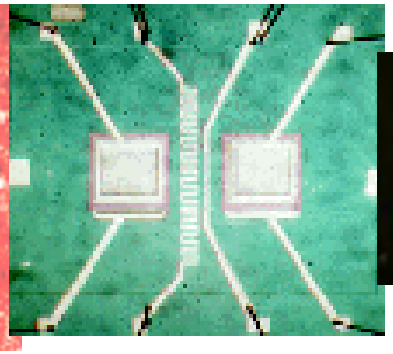
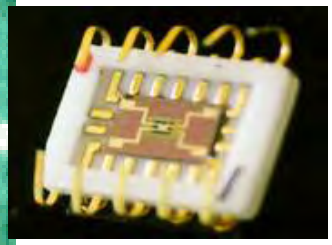
NDE



Electro-Optics & Mobile Sensors

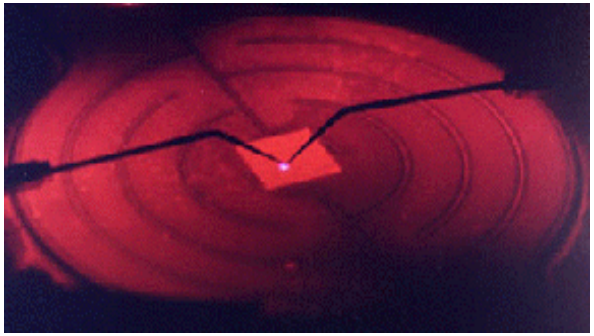
SENSORS AND ELECTRONICS TECHNOLOGY BRANCH
SCOPE OF WORK



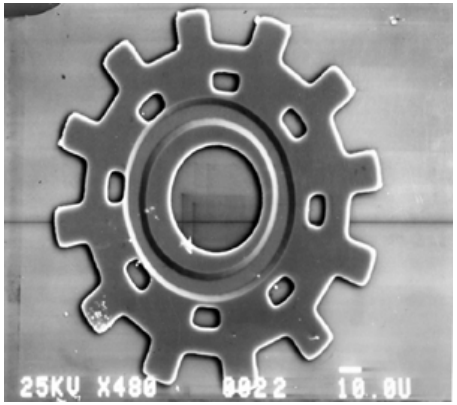




PHYSICAL SENSORS (T, Strain, Heat Flux)

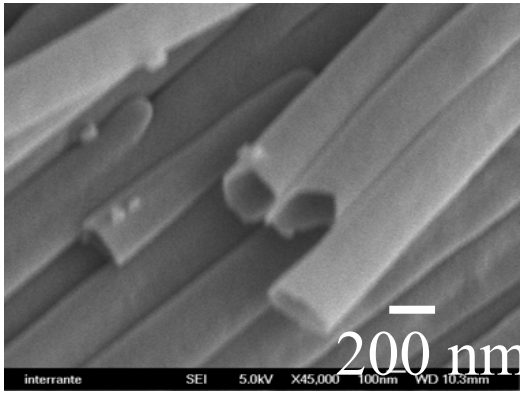
CHEMICAL SENSORS



SILICON CARBIDE HIGH TEMP ELECTRONICS



MICRO-ELECTRO-MECHANICAL SYSTEMS

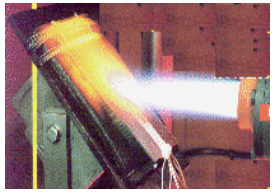


NANOTECHNOLOGY

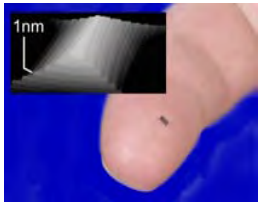
CUTTING EDGE DEVELOPMENT HARSH ENVIRONMENT SENSORS AND ELECTRONICS

HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

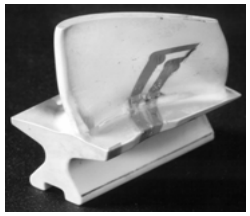
- NEEDS:
  - OPERATION IN HARSH ENVIRONMENTS
  - RANGE OF PHYSICAL AND CHEMICAL MEASUREMENTS
  - INCREASE DURABILITY, DECREASE THERMAL SHIELDING, IMPROVE IN-SITU OPERATION
- RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES
  - STANDARD 500C OPERATION BY MULTIPLE SYSTEMS
  - TEMPERATURE, PRESSURE, CHEMICAL SPECIES, WIND SENSOR SYSTEMS AVAILABLE
  - HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS
- ALL-IN-ONE SHOP FOR HARSH ENVIRONMENT SYSTEM APPLICATIONS
- ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS



1998 R&D 100 Award



2004 R&D 100 Award

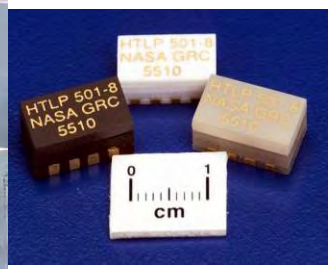


1995 R&D 100 Award

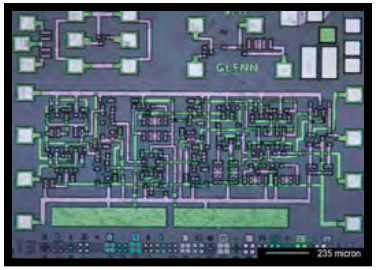
1991 R&D 100 Award

Range of Physical and Chemical Sensors for Harsh Environments

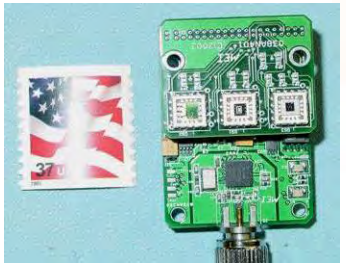
Harsh Environment Packaging (2000 hours at 500C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems

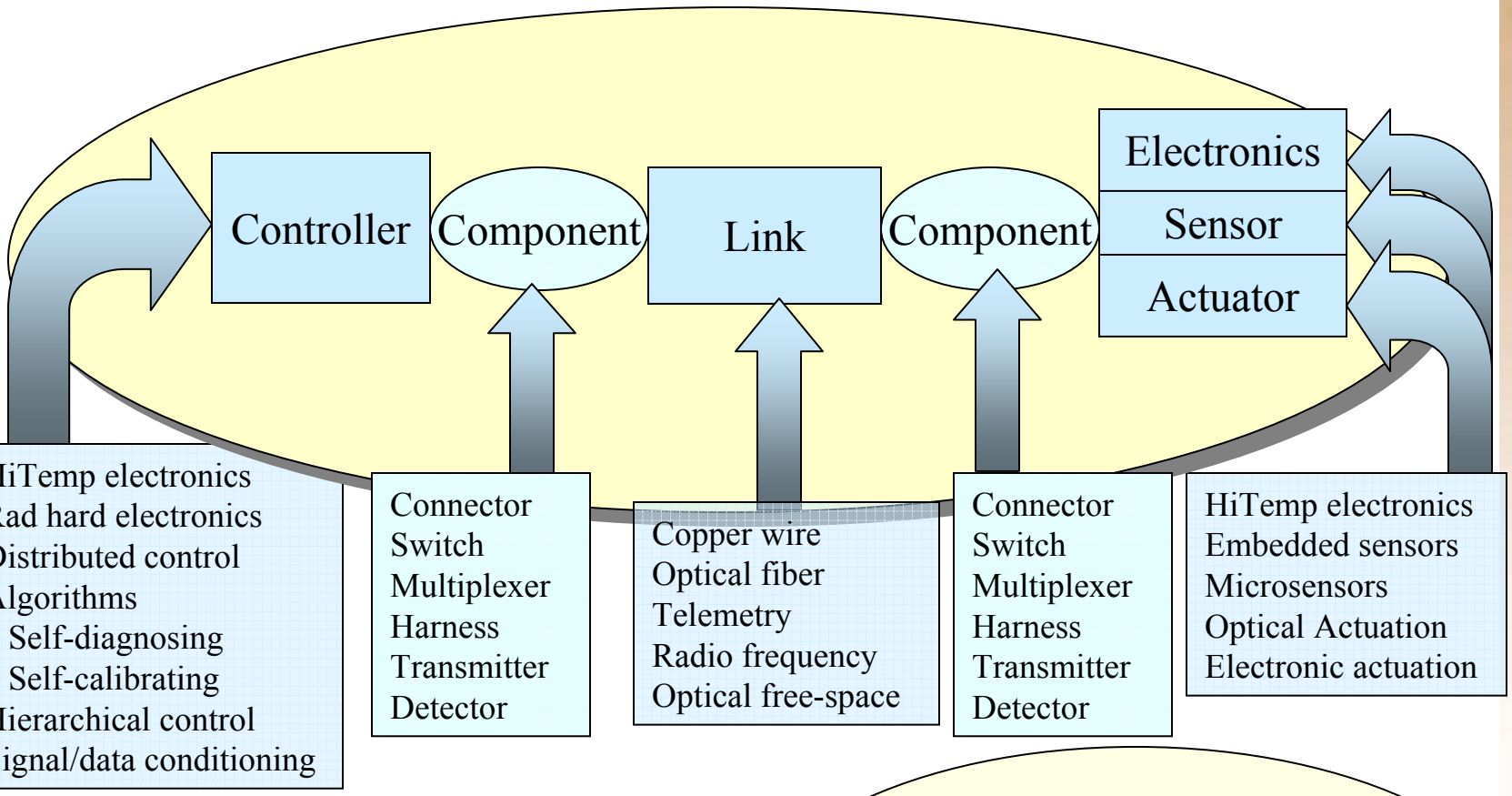


BASIC APPROACH:
MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS

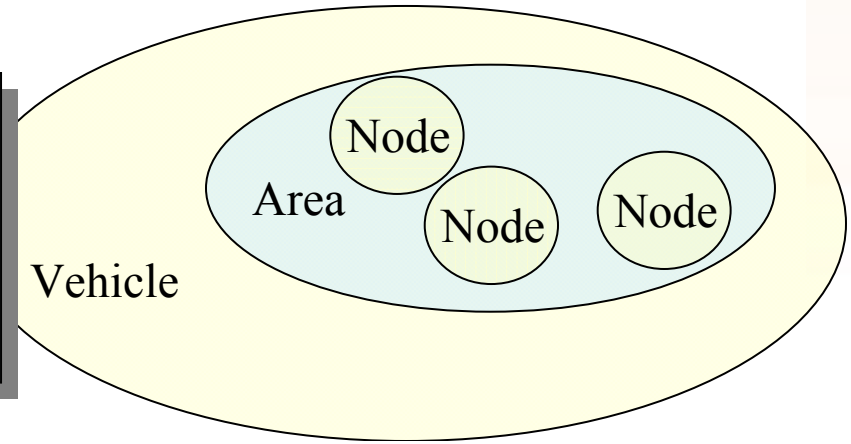
POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS

- **TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER/TAILOR SENSOR FOR NEEDS OF APPLICATION**
  - **Deliverables/budget/time frame are typically application and vehicle dependent. Sensors should be included at the beginning of the design process rather than as an afterthought**
- **"LICK AND STICK" TECHNOLOGY (EASE OF APPLICATION)**
  - **Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.**
- **RELIABILITY:**
  - **Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations e.g. decreasing sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur if it can be trusted.**
- **REDUNDANCY AND CROSS-CORRELATION:**
  - **If the systems are easy to install, reliable, and not increase weight/complexity, the application of a large number of them is not problematic. This allows redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.**
- **ORTHOGONALITY:**
  - **Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to "see, feel, smell, hear" as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.**

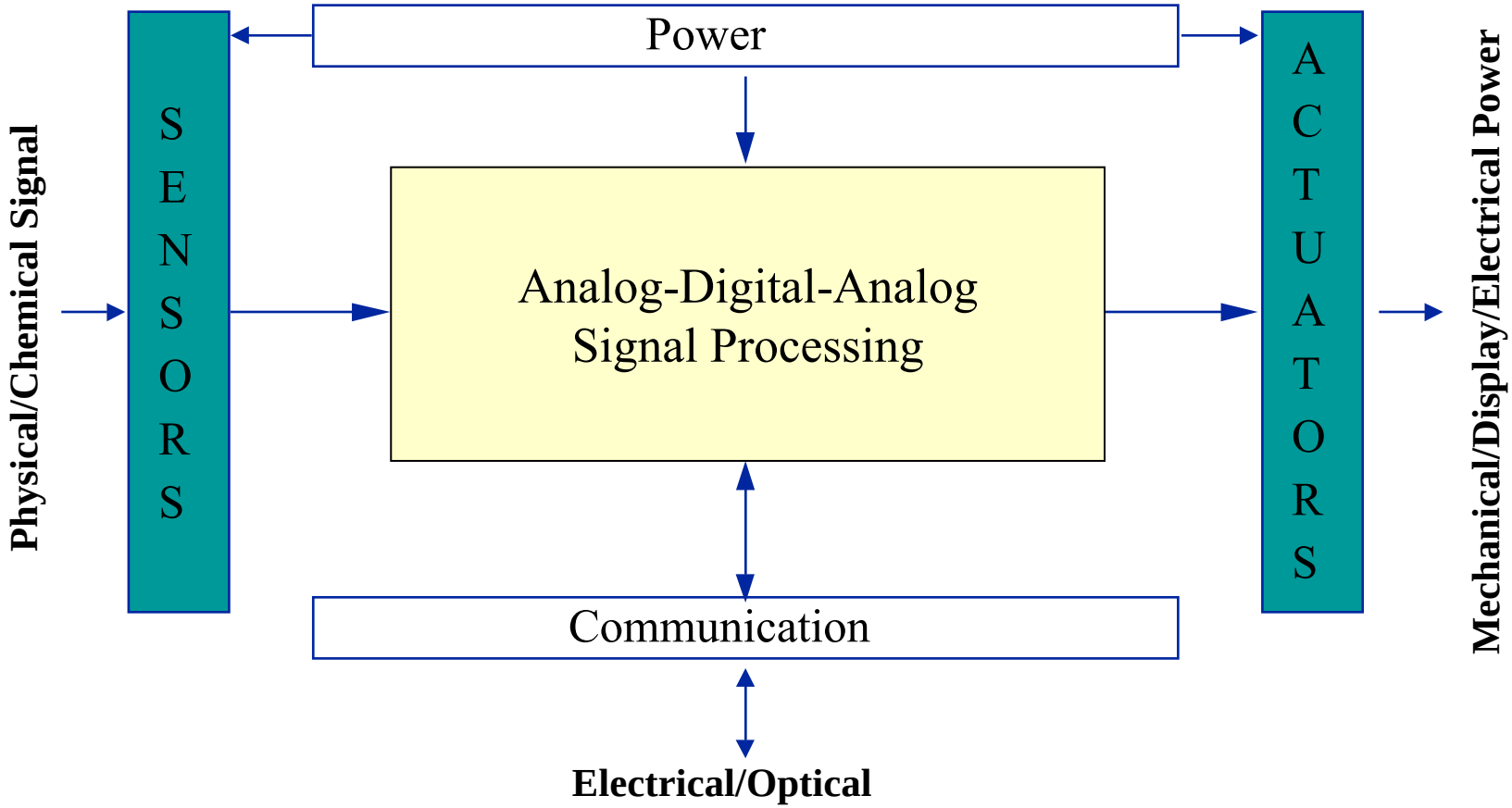
Localized Avionics System Infrastructure



Improve system ***reliability***, ***cost***, and ***weight*** by using **local avionics elements** for distributed, smart sensing and control. Link local nodes to areas, then integrate entire vehicle using hierarchical design.



MICROSYSTEM TECHNOLOGY



IVHM Program:
High Temperature Sensors, Electronics, And Communications

Enable New Capabilities …

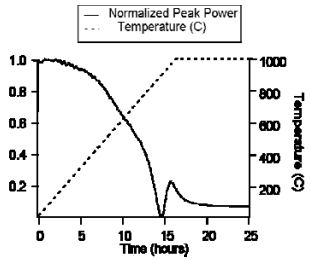
- Propulsion Structural Health Monitoring
- High-temperature Pressure Sensors and
- High-temperature Wireless Communications And Energy Harvesting Technologies

Technical Approach:

- Propulsion structural health monitoring including smart accelerometers, and optical strain and blade tip-timing sensors.
- Pressure sensors for incorporation into gas-path trending and fault diagnostic models to infer turbine health.
- Integration of sensor technology with high temperature wireless communications and energy harvesting to enable a smart systems operable at high temperatures.
  - ➢ High-temperature wireless communications based on SiC electronics and rugged RF passive components
  - ➢ Energy harvesting systems focusing thermo-electric and photo-voltaic materials for generation of power for remote sensors.

High Temperature Pressure Sensor

Self Diagnostic Accelerometer

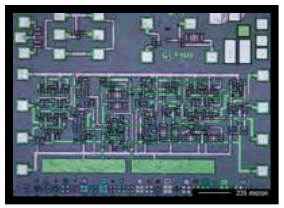


High Temp Fiber Sensor Operation

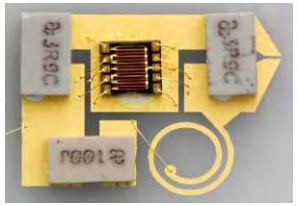
Provide a New Generation of Sensor Technology

Significant wiring exists with present sensor systems

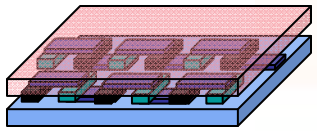
Allow Sensor Implementation by Eliminating Wires



World Record High Temperature Electronics Device Operation



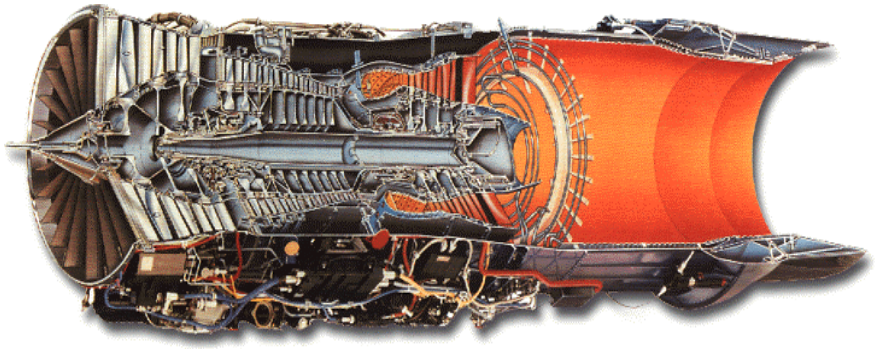
High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

HIGH TEMPERATURE ELECTRONICS AND SENSORS BENEFITS TO NASA MISSIONS

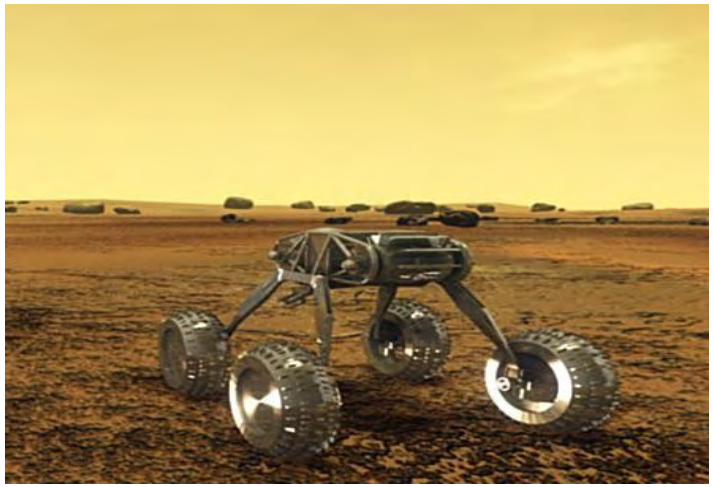
Intelligent Propulsion Systems



Space Exploration Vision PMAD

More Electric + Distributed Control Aircraft

Venus Exploration

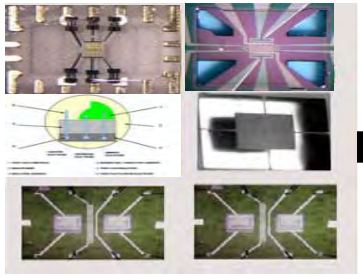


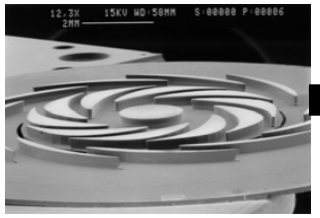
HARSH ENVIRONMENT VENUS MISSION REQUIREMENTS

- **SURFACE CONDITIONS**
  - **TEMPERATURE: 450-500 C**
  - **PRESSURE: 90 bar PREDOMINATELY (~100 TIMES EARTH)**
  - **SULFURIC ACID PARTICLES IN CLOUD DECK**
  - **96.5% CO_2 and 3.5% N_2; Trace Gases include H_2O, SO_2, CO, HCl, H_2, and HF**
- **SOME PARAMETERS OF INTEREST: TEMPERATURE, PRESSURE, CHEMICAL SPECIES, FLOW (WIND)**
- **TEMPERATURE CONTROL INCREASES SYSTEM COMPLEXITY/RISK TO MISSION**
- **NEED TO SHIELD SYSTEM FROM EXTREME ENVIRONMENTS YIELDS INCREASE IN SIZE AND WEIGHT**
- **LIMITED INFORMATION AVAILABLE FROM IN-SITU SYSTEMS DUE TO HARSH ENVIRONMENTS INVOLVED**
- **SCIENTIFIC COMMUNITY: LACK OF VIABLE HARSH SENSOR SYSTEMS SENSORS AND ELECTRONICS FOR IN-SITU CHARACTERIZATION**

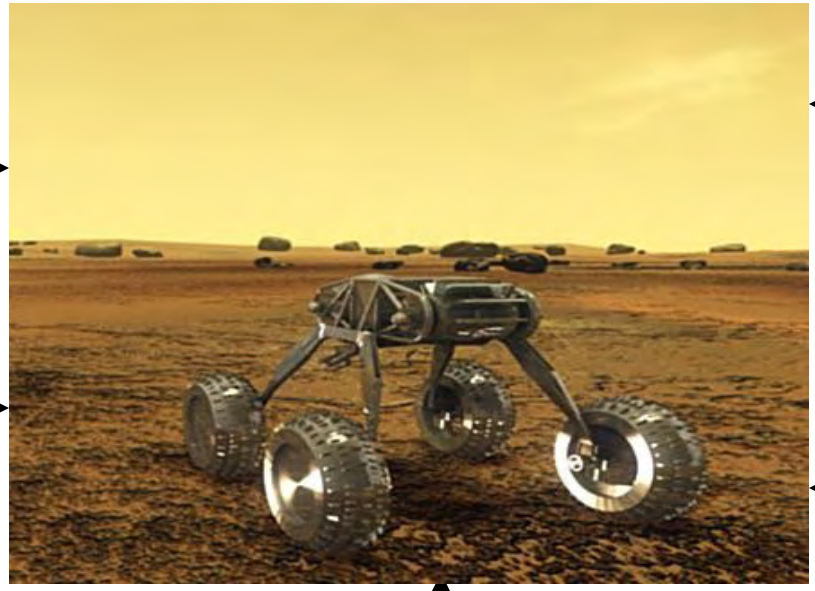
VENUS LONG DURATION IN-SITU SCIENTIFIC MISSIONS LIMITED BY AVAILABILITY OF HARSH ENVIRONMENT SENSORS AND ELECTRONICS

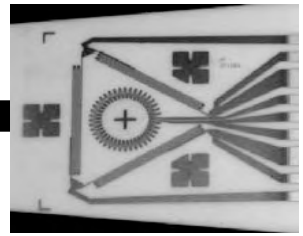
THIS TALK DISCUSSES A RANGE OF HIGH TEMPERATURE TECHNOLOGY RELEVANT TO VENUS OPERATIONS





HIGH TEMPERATURE ELECTRONIC NOSE

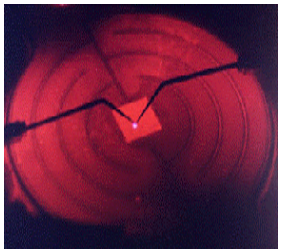




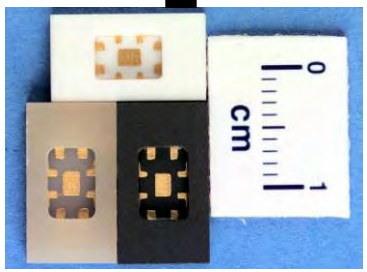
MULTIFUNCTIONAL PHYSICAL SENSOR ARRAY

600°C PRESSURE SENSOR

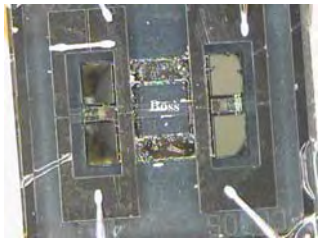
MICROENGINE, ACTUATORS, AND FUEL DELIVERY



HIGH TEMPERATURE MICROELECTRONICS



HIGH TEMP PACKAGING



Hi-g SiC ACCELEROMETER

High Temperature Semiconductor Electronics

Above 400 °C ambient, wide bandgap semiconductors are needed
- Beyond physical limits of bulk silicon and silicon-on-insulator.

CRITICAL REQUIREMENT: High Temperature Electronics must operate **DURABLY AND RELIABLY** in order to be useful to most applications.

Parts that work for only a few minutes, hours or days at desired high temperature **are not** useful components for most applications.

> 1,000 hours at temperature a starting point for turbine engine ground test.

> 100,000 hours needed for vast majority of aviation and space exploration.

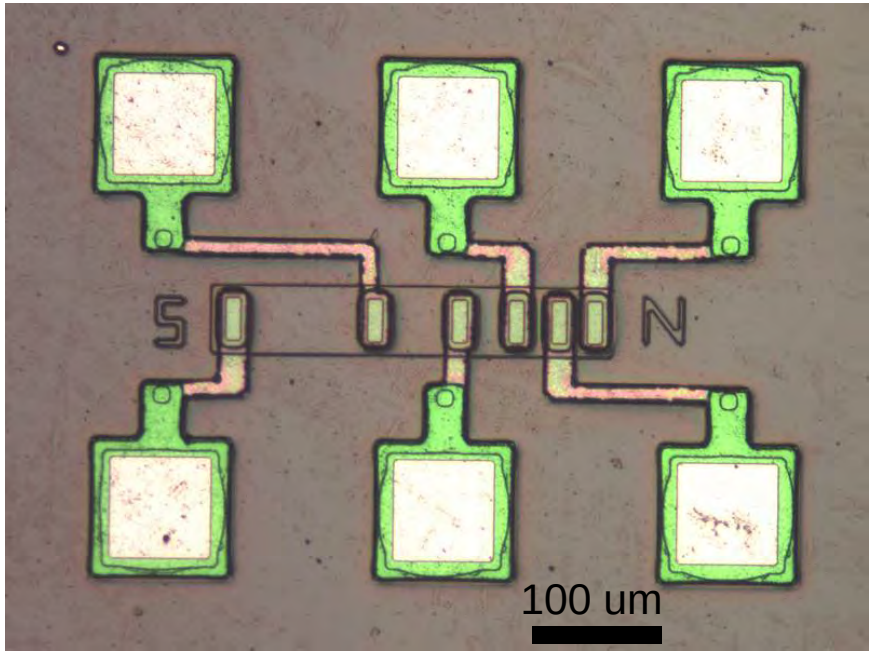
Of the numerous examples of wide bandgap semiconductor transistor demonstrations in the published literature, none have demonstrated stable electrical operation beyond a few hours at T ≥ 500 °C.

NASA Program Goal: Realization of highly durable 500-600 °C SiC electronics for sensor signal conditioning and digital logic.

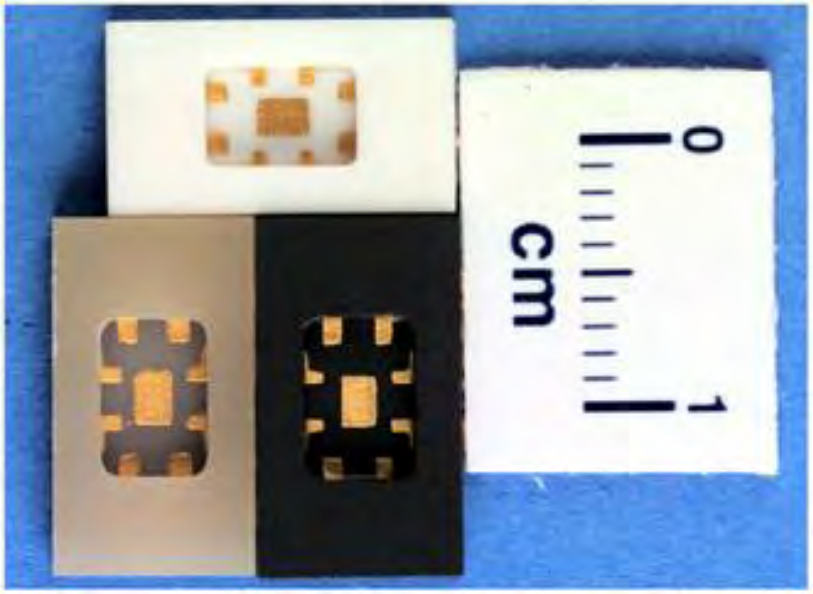
Previous Key NASA Glenn Advancements

Key fundamental high temperature electronic materials and processing challenges have been faced and overcome by systematic basic materials processing research (fabrication and characterization).

500 °C Durable Metal-SiC Contacts
(R. Okojie, 2000 GRC R&T Report)



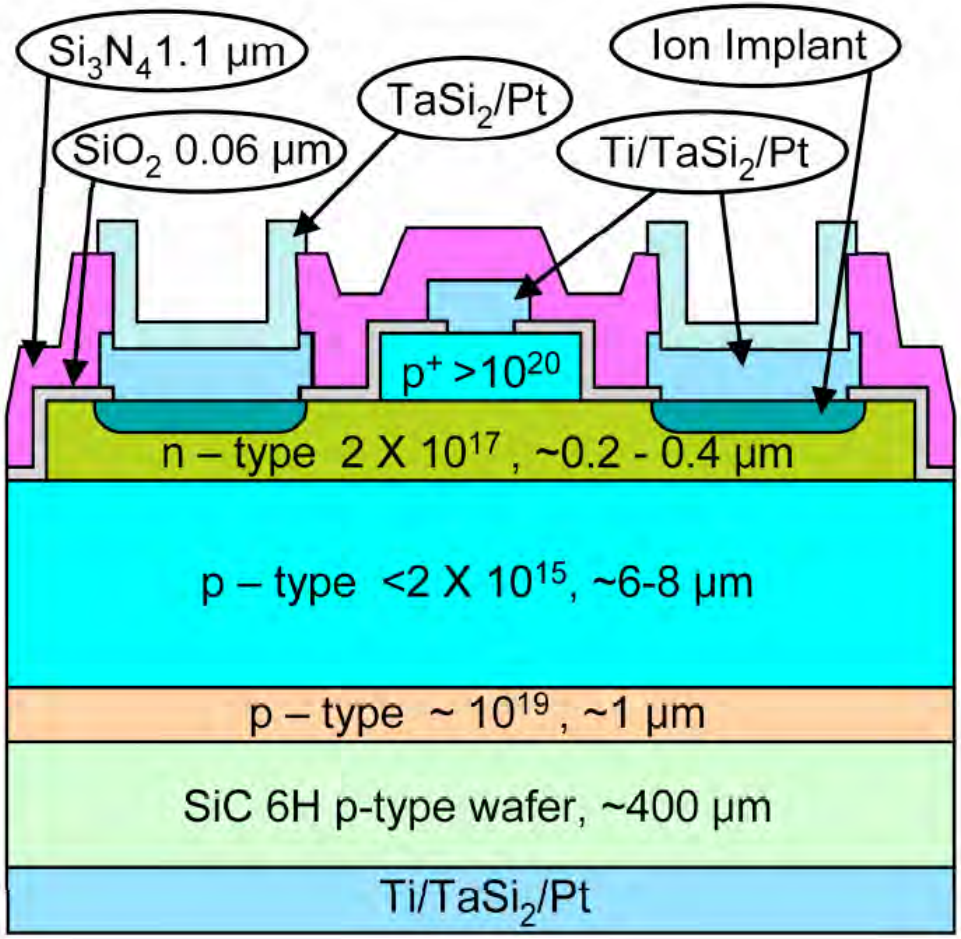
500 °C Durable Chip Packaging
And Circuit Boards
(L. Chen, 2002 GRC R&T Report)



Additional advancements in device design, insulator processing, etc. also made.

SiC Transistor Structure

6H-SiC Junction Field Effect Transistor (JFET)



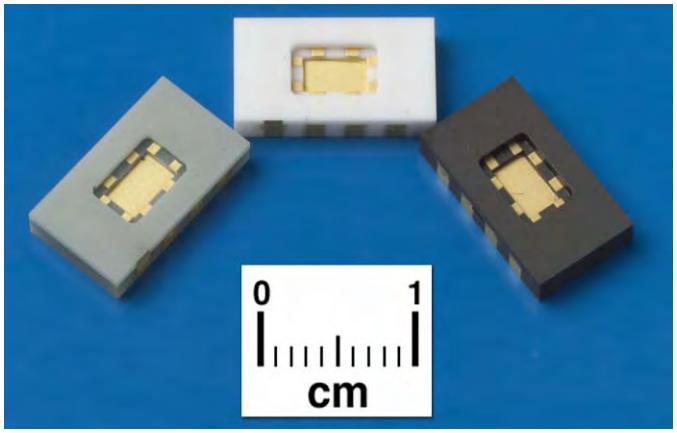
- 6H p-type SiC wafer with epilayers (purchased from Cree)
- Two p-type epilayers
  - ~10^{19}, ~ 1 µm (buffer layer)
  - ~10^{15}, ~ 6-8 µm
- n-type channel
  - 1-2x10^{17}, ~0.2-0.4 µm
- p^+ gate ~10^{20}, ~ 0.14 µm
- Ti/$TaSi_2$/Pt electric contact
- Oxide (wet rewet) and nitride passivation
- Triple-layer contact on the backside of wafer
- $TaSi_2$/Pt interconnect metal (single layer interconnect)
- Metal patterning was dry/wet no ion damage to dielectric

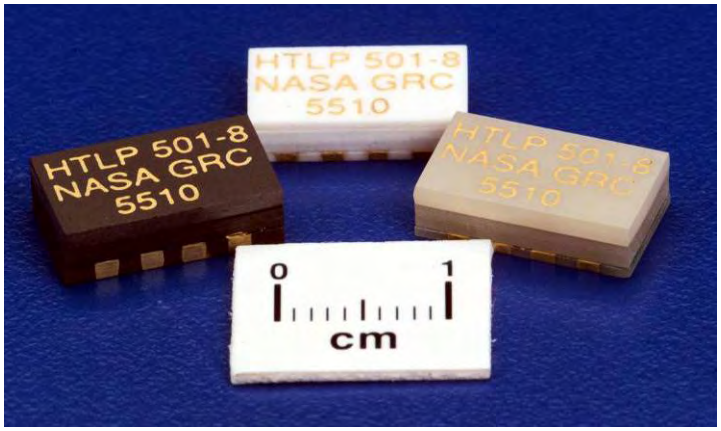
JFET chips enabled by development <u>and</u> integration of new SiC processes.

Chip Level Packages for 500°C Application

96% Al_2O_3

AlN



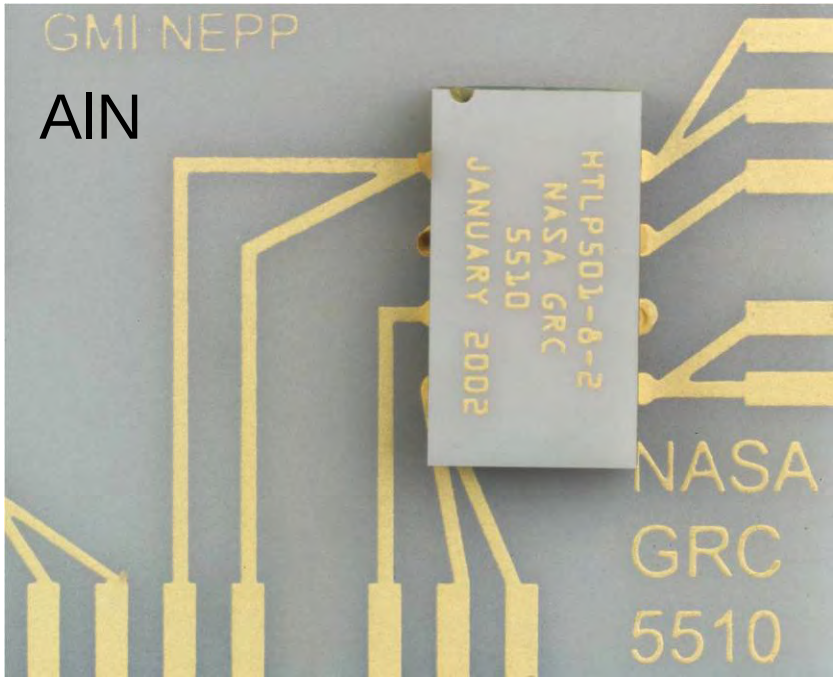


90%
Al_2O_3

- Three types of ceramic substrate and Au thick-film metallization based chip-level packages
- A compatible low resistance die-attach scheme tested for 1000hrs
- Compatible printed circuit board level interconnection system developed

Circuit Board Level Interconnection

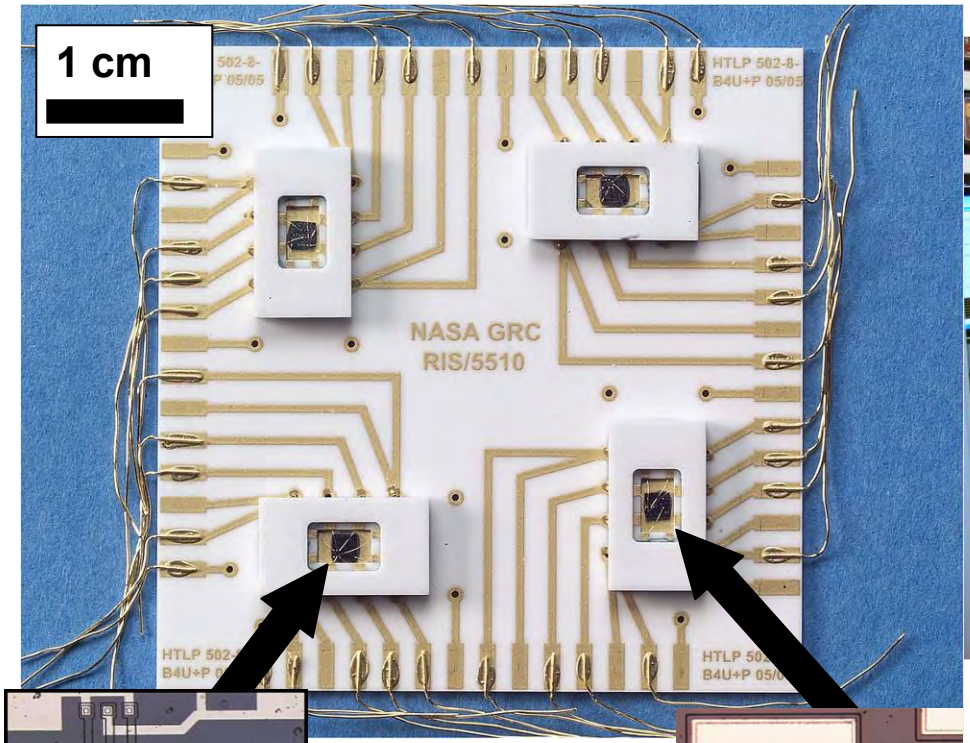
Electronic Package for High Temperature Micro-Systems

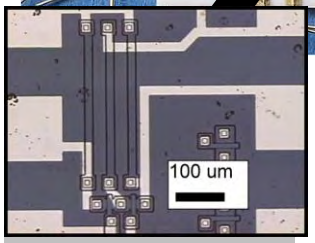


- Three types of ceramic substrate and Au thick-film metallization based PCB
- Interconnection between chip-level packages and PCB
- 500 C technology

Packaged Devices and Test Setup

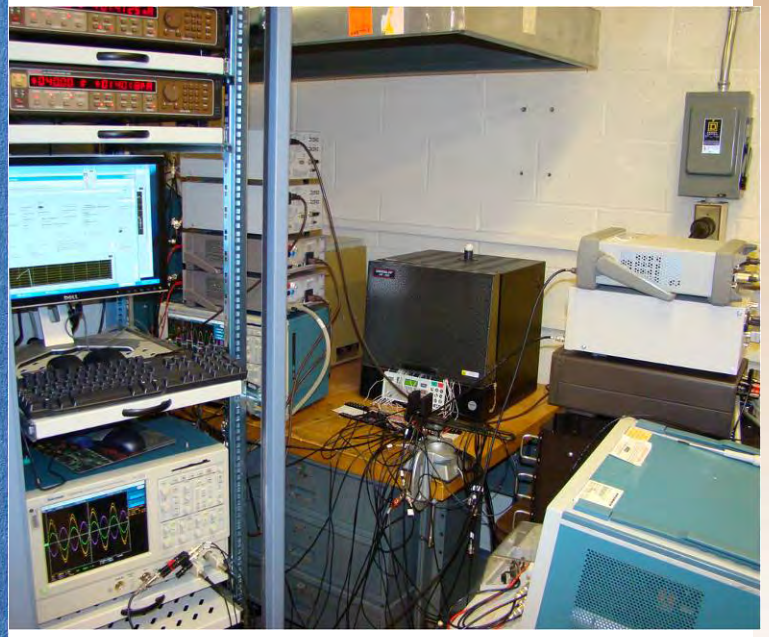
Parallel fabrication and testing of both single-transistors and IC's





Differential Amplifier

200µm/10µm 6H-SiC JFET



Boards with chips reside in ovens.

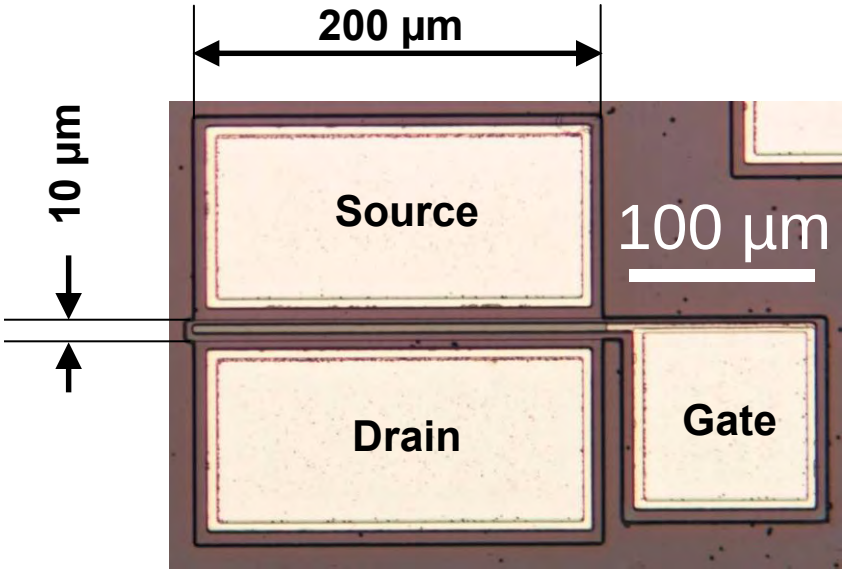
Oxidizing atmospheric air at 500 °C.

Wires to test instrumentation.

Continuous electrical testing at 500 °C.

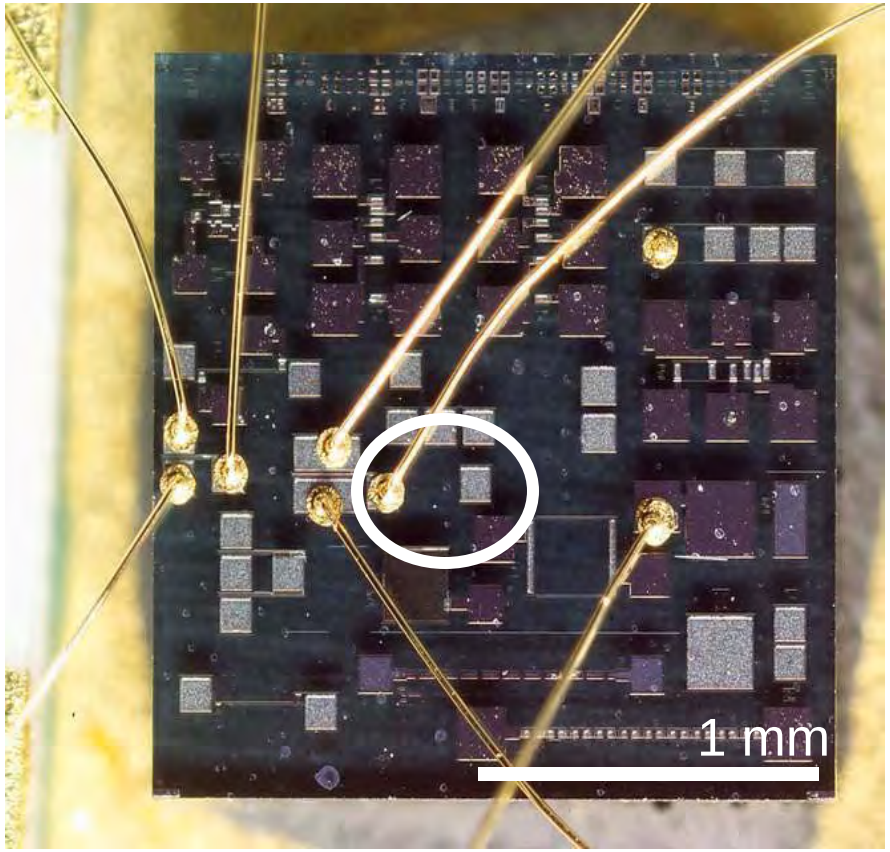
6H-SiC Junction Field Effect Transistor (JFET) Fabricated by NASA Glenn Research Center

200μm/10μm 6H-SiC JFET



Optical micrograph of device before packaging

Packaged with bond wires



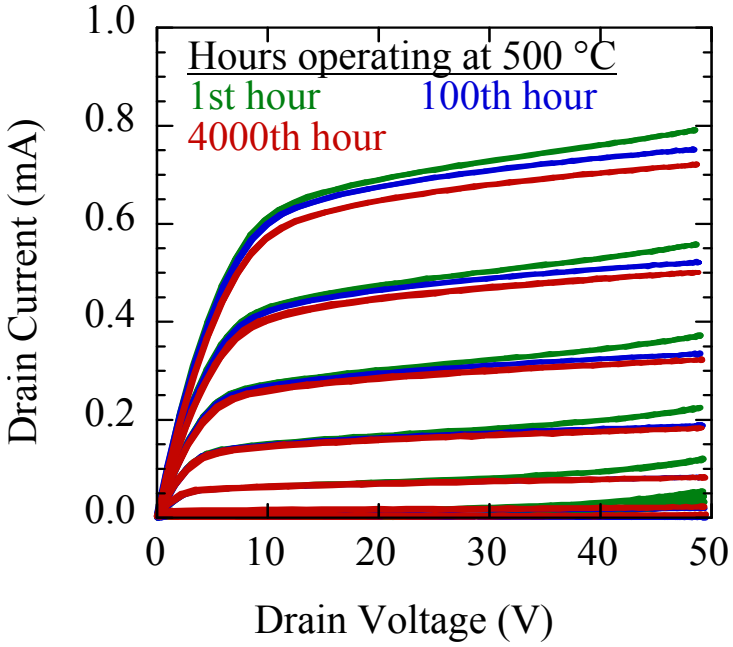
NASA Glenn SiC JFET

First Transistor to Surpass 4000 Hours of Stable Electrical Operation at 500 °C

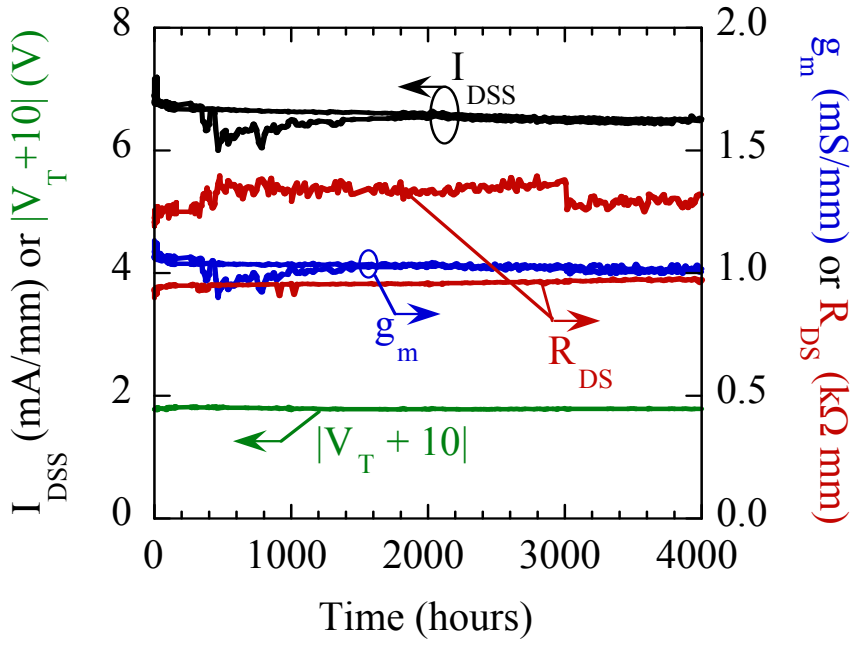
Current-voltage characteristics are very good and stable after 4000 hours.
- Enables realization of analog integrated circuits (amplifiers, oscillators).

Excellent turn-off characteristics, large ON to OFF current ratio (> 1000).
- Enables realization of digital logic circuits.

Current vs. Voltage Characteristics



Key Parameters vs. Time @ 500 °C



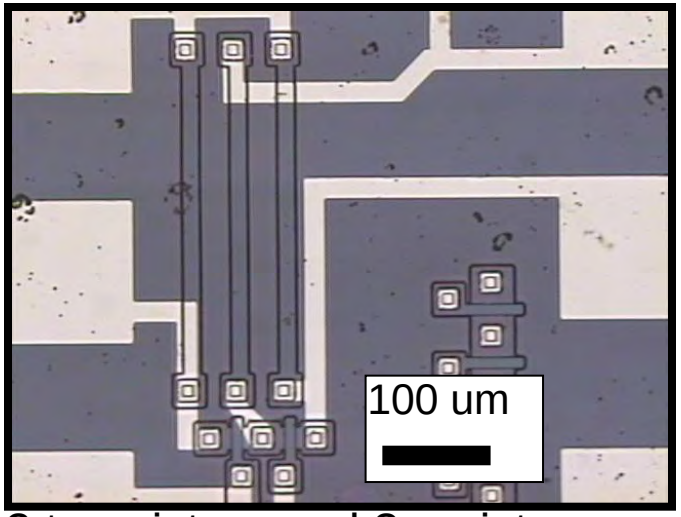
Less than 10% change occurs during 4000 hours at 500 °C (most during 1st 100 hrs).
- 10% variation is smaller than listed on most silicon transistor spec. sheets.

NASA Glenn Silicon Carbide Differential Amplifier

World's First Semiconductor IC to Surpass 4000 Hours of Electrical Operation at 500 °C

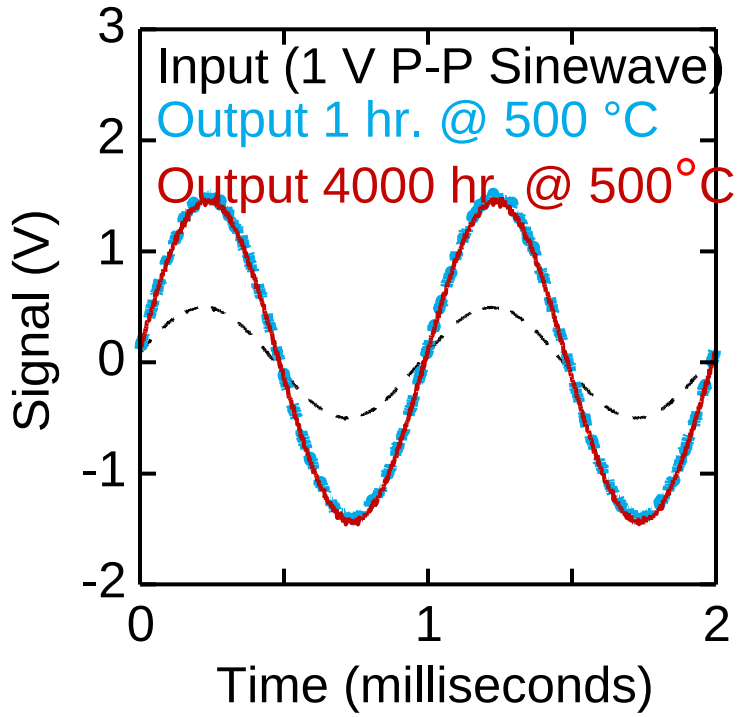
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500 °C.

Optical micrograph of demonstration amplifier circuit before packaging



2 transistors and 3 resistors integrated into less than half a square millimeter.
Single-metal level interconnect.

Test waveforms at 500 °C

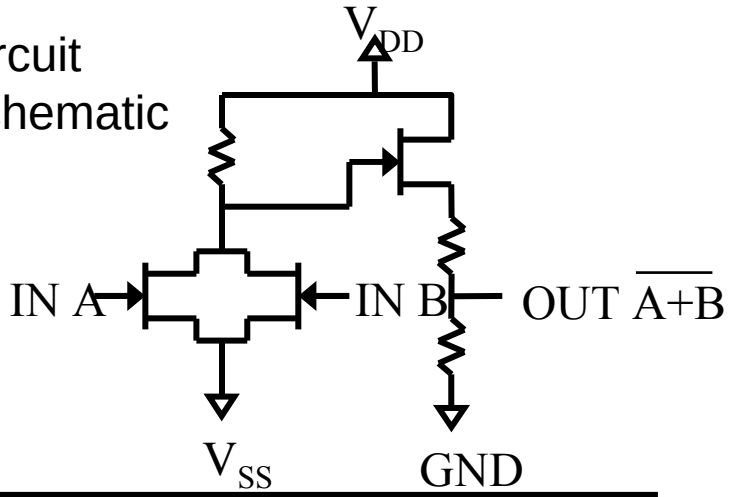


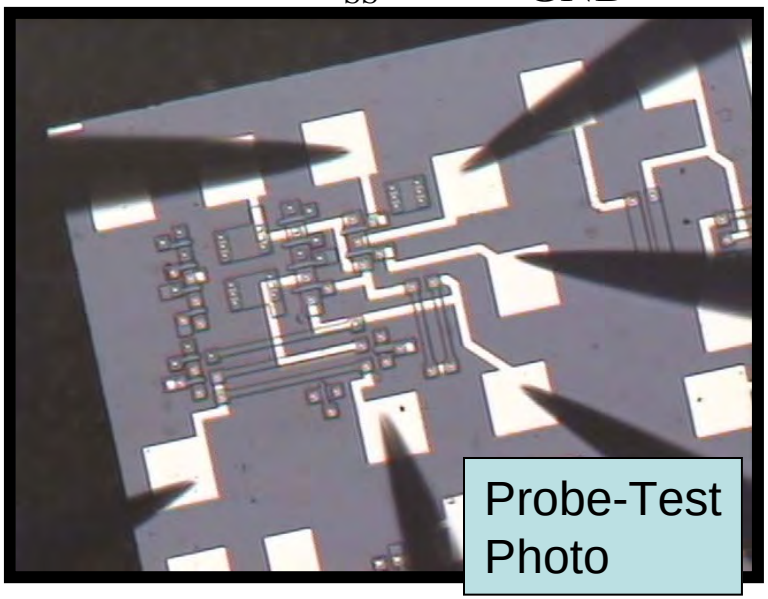
Less than 5% change in operating characteristics during 4000 hours of 500 °C operation.

NASA Glenn SiC JFET NOR Gate IC

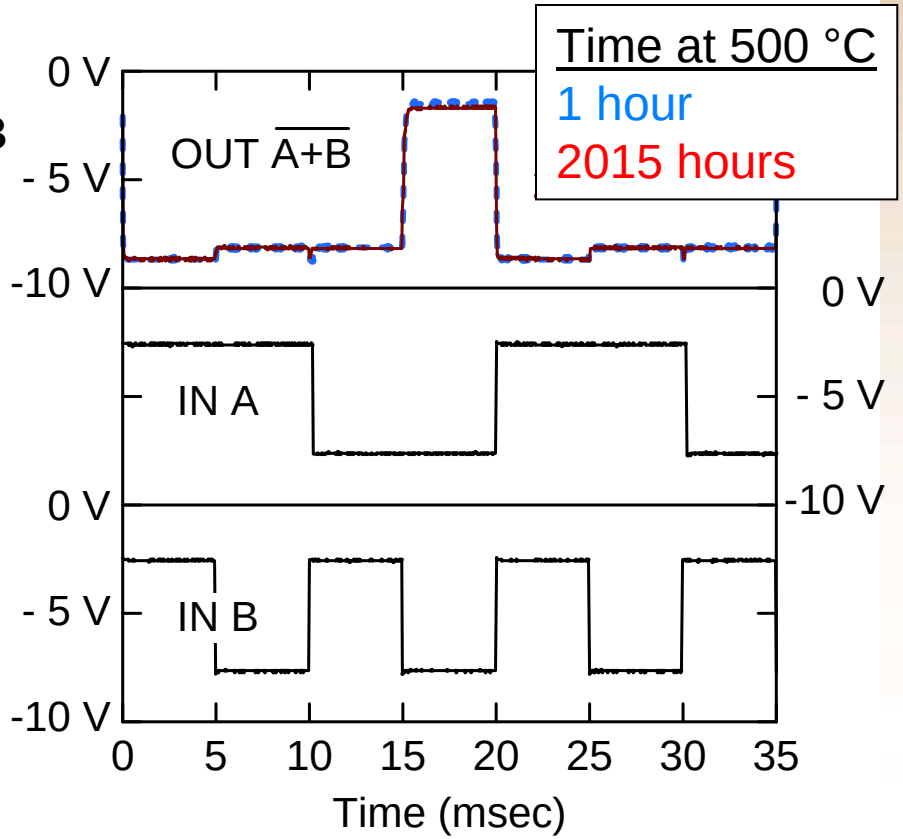
World's First Semiconductor Digital IC to Surpass 2000 hours of 500° C Operation

Circuit Schematic





Waveforms of **packaged** NOR (= "Not OR") gate at 500 °C



SIGNIFICANCE OF RECENT ELECTRONICS RESULTS
THE BASIC HARDWARE TOOLS FOR HIGH TEMPERATURE DATA PROCESSING HAVE BEEN FABRICATED

- **THESE RESULTS HAVE BEEN THE SUBJECT OF A HIGH LEVEL OF VISIBILITY E.G. NASA TOP 10 DISCOVERY STORIES FOR 2007**
- **DURABLE HIGH TEMPERATURE IC'S WILL ENABLE IMPORTANT NEW CAPABILITY**
  - Enabled by fundamental electronic materials research.
  - World record IC durability at 500 °C (> 700-fold improvement).
  - Inherently up-scalable to high circuit complexity while remaining physically small.
- **THIS DEMONSTRATION SHOWS THAT IT IS NOW POSSIBLE TO CONSTRUCT MORE COMPLEX CIRCUITS OPERATING AT 500 °C AND MINIATURIZED.**
- **LOGIC GATES GENERATE FLIP-FLOPS THAT CAN GENERATE STATE-MACHINES TO ENABLE:**
  - Creation Of Control Electronics For An "Intelligent" Fixed Or Mobile Agent
  - The Configuration Of Intelligent Data Transmission Methods Allowing For Unambiguous Demodulation Of Signals Uniquely Associated With Each Sensor/Transmitter In A Network.
- **OBJECTIVE: TO MOVE TOWARD HIGHER DEGREES OF COMPLEXITY ALLOWING WIRELESS TRANSMISSION**

High Temperature Wireless Development

OBJECTIVES:

- **HIGH TEMPERATURE WIRELESS TELEMETRY, DISTRIBUTED ELECTRONICS OVER A BROAD OPERATING RANGE**

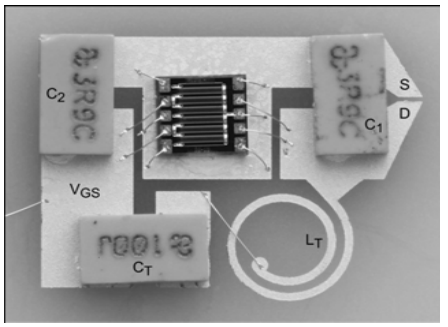
- **TECHNICAL CHALLENGES: DEVELOPMENT OF RELIABLE HIGH TEMPERATURE TELEMETRY ELECTRONICS, POWER SOURCES, REMOTE COMMUNICATION ELECTRONICS, AND PACKAGING**

- **PROVIDE DATA TRANSFER IN HARSH ENVIRONMENTS IMPROVING RELIABILITY AND ENABLING NEW CAPABILITIES**

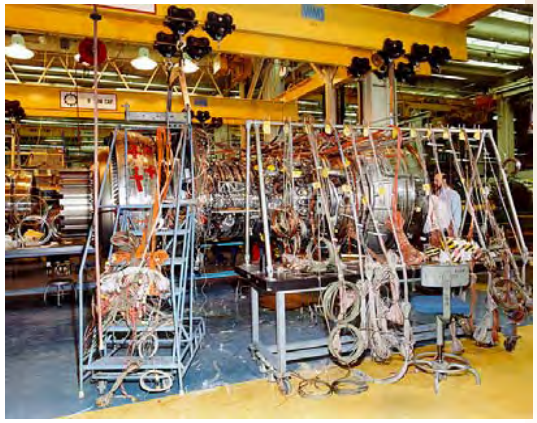
- **OVERALL APPROACH: SMART SYSTEMS IN HIGH TEMPERATURE ENVIRONMENTS**

- **MILESTONE: DEMONSTRATE HIGH TEMPERATURE SENSING, WIRELESS COMMUNICATION, AND POWER SCAVENGING FOR PROPULSION HEALTH MANAGEMENT 8/30/2011**

- **METRIC: DEMONSTRATE INTEGRATED SELF POWERED WIRELESS SENSOR SYSTEM AT 500 C WITH DATA TRANSMISSION OVER 1 M DISTANCE MINIMUM AND OPERATIONAL LIFE OF AT LEAST 1 HR**



Prototype Oscillator Circuit

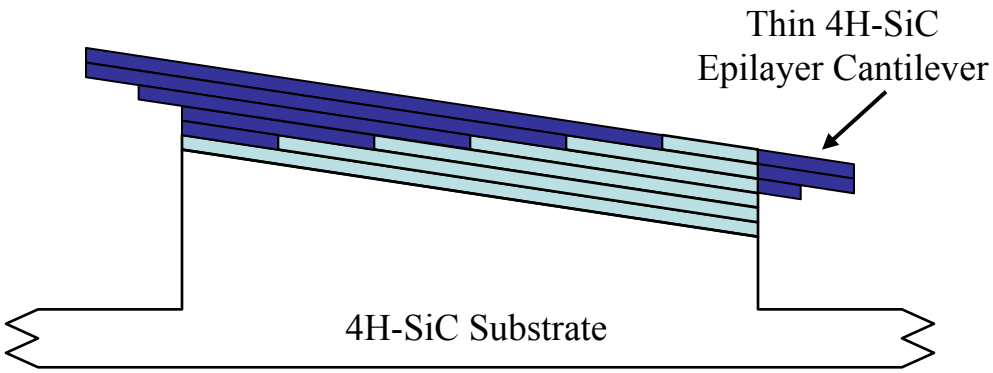


Wires from 1000 Sensors

Example: Gas Turbine Engine Development Requires Extensive Instrumentation Yielding Extensive Wiring Complexity

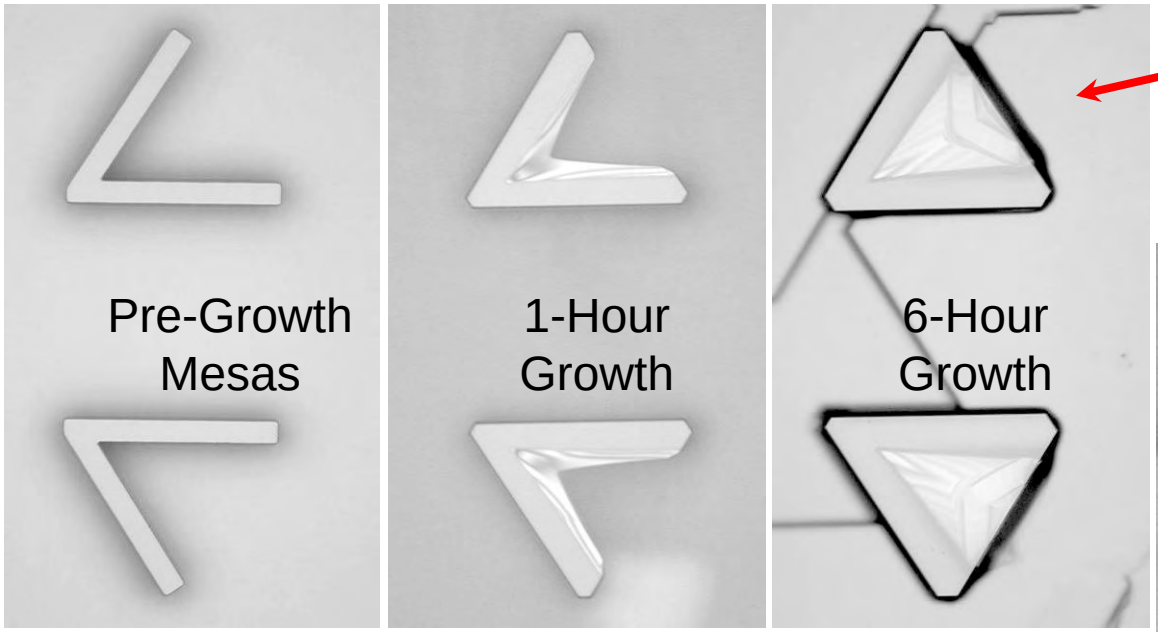
Atomically Flat SiC Mesas and Cantilevers

P. G. Neudeck et al., J. Appl. Phys. 92 p. 2391 (2002).

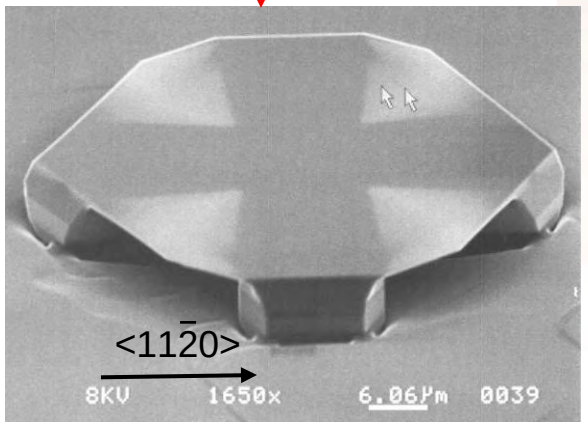


Top surface of mesa is atomically smooth completely free of steps. Surface can be enlarged by growing defect-free cantilevers.

Defect-free areas large enough for prototype devices!



Atomically Flat "Webbed Cantilevers"

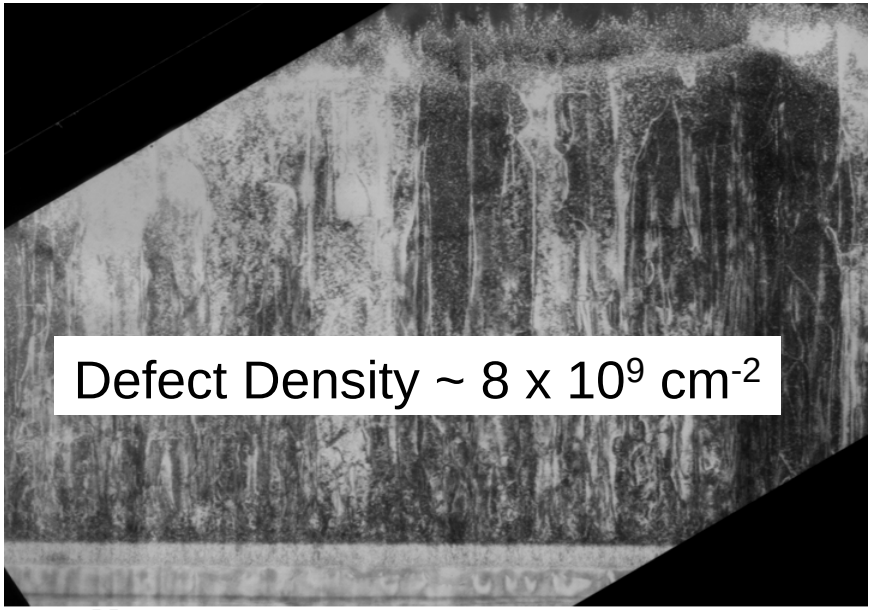


Accomplishment: Growth of Improved GaN on SiC Films

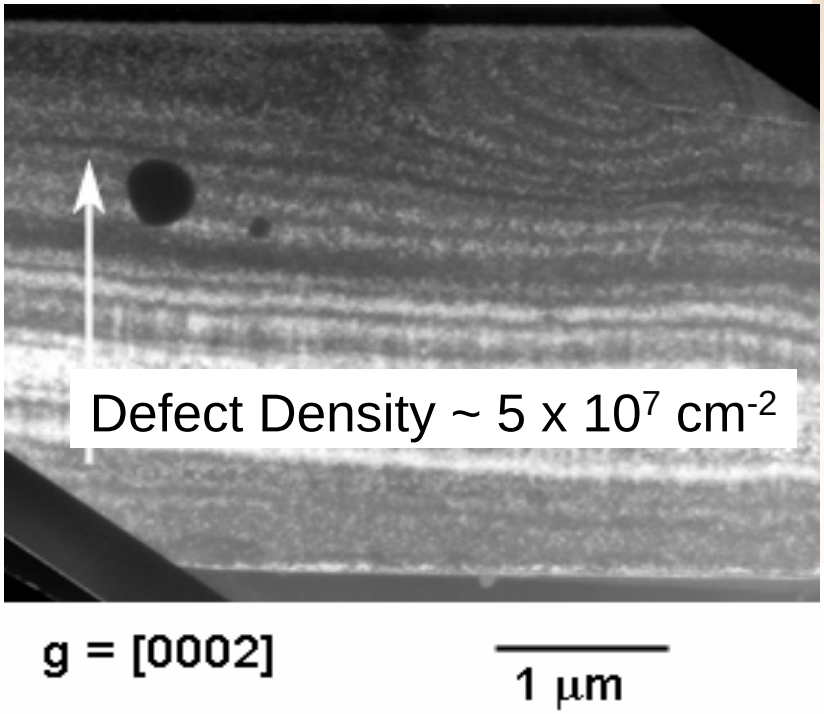
Method: Growth of GaN (by US Naval Research Laboratory) on top of Atomically Flat SiC Mesa Arrays Grown by NASA GRC.

Transmission Electron Micrographs (from NRL) Comparing GaN on SiC Films

GaN grown on top of conventional SiC with surface steps



GaN grown on top of NASA GRC SiC mesa free of surface steps



GaN Dislocation Density Reduced by 100X!

SiC-BASED GAS SENSOR DEVELOPMENT

- THE USE OF SiC SEMICONDUCTORS ALLOWS SENSOR OPERATION AT TEMPERATURES WHICH ALLOW THE DETECTION OF HYDROCARBONS AND NOx
- SCHOTTKY DIODE DESIGN FOR HIGH SENSISTIVITY
- TEMPERATURE DETECTOR AND HEATER INCLUDED

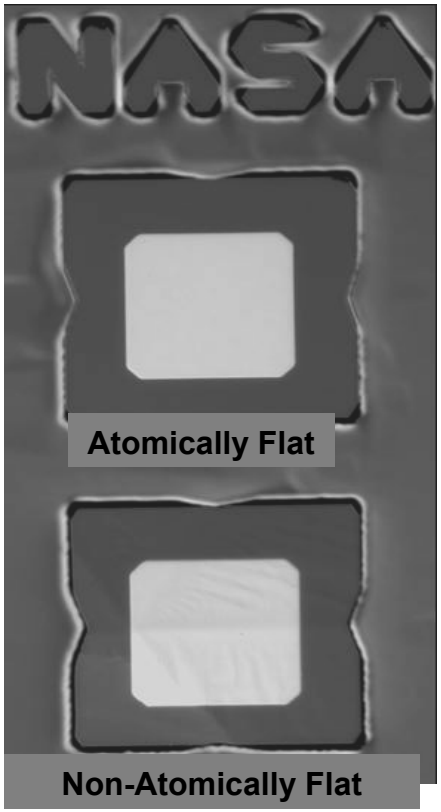
  OPERATION AT A RANGE OF TEMPERATURES
- WIDE RANGE OF APPLICATIONS

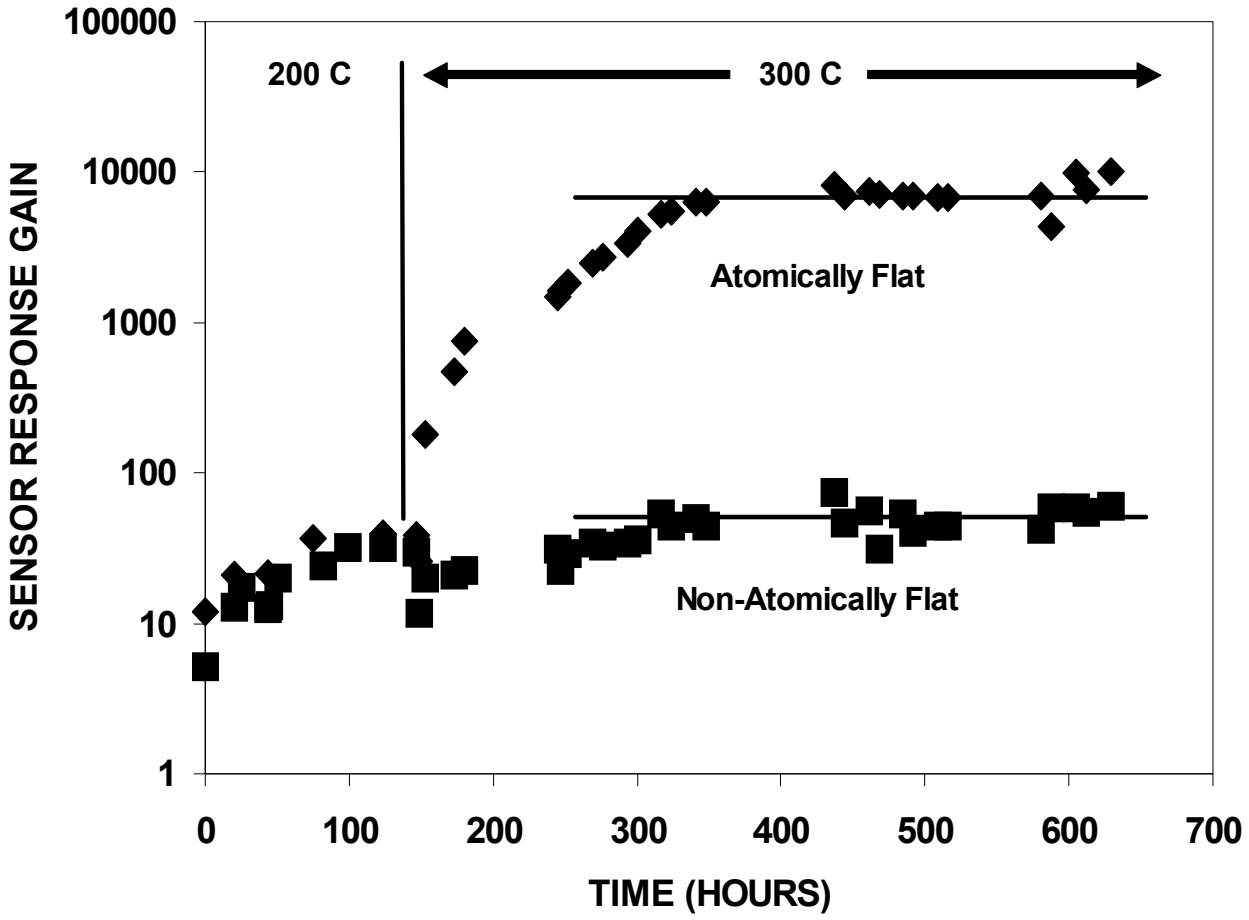
  EMISSION MONITORING
  ENGINE HEALTH MONITORING
  ACTIVE COMBUSTION CONTROL
  HYDROCARBON FUEL LEAK DETECTION
  FIRE SAFETY
- PROTOTYPE SENSOR PACKAGE FABRICATED
- ONE MAJOR ISSUE IS THE ROUGHNESS OF THE SiC SURFACE
  - •SURFACE DEFECTS AFFECT PERFORMANCE
  - •MOVE TOWARDS THE USE OF ATOMICALLY FLAT SiC

PACKAGED SiC-BASED SENSOR

Pt/SiC SCHOTTKY DIODES TESTED SIDE BY SIDE ON SAME CHIP: ATOMICALLY FLAT AND NON-ATOMICALLY FLAT

WORLDS FIRST DEMONSTRATION OF GAS SENSORS ON ATOMICALLY FLAT SiC





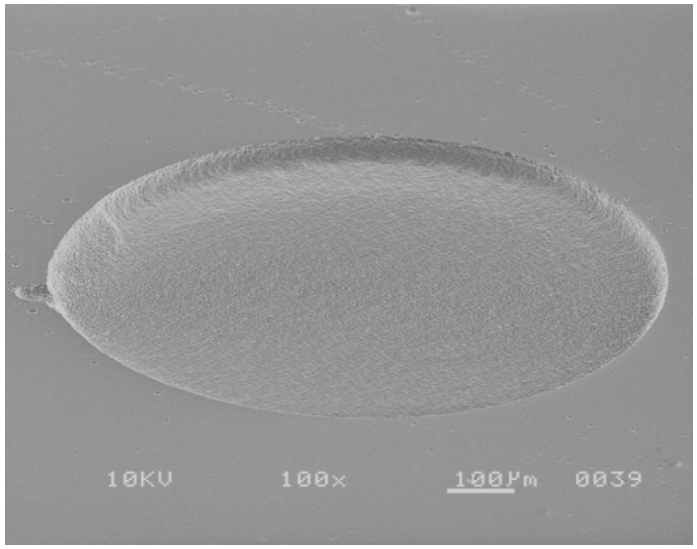
COMPARISON OF SENSOR GAIN TO 0.5% HYDROGEN BETWEEN Pt/SiC SENSORS DEPOSITED ON ATOMICALLY FLAT SIC (♦) AND NON-ATOMICALLY FLAT SIC (■)

SiC MICROMACHINING

SiC is chemically inert and therefore difficult to micromachine

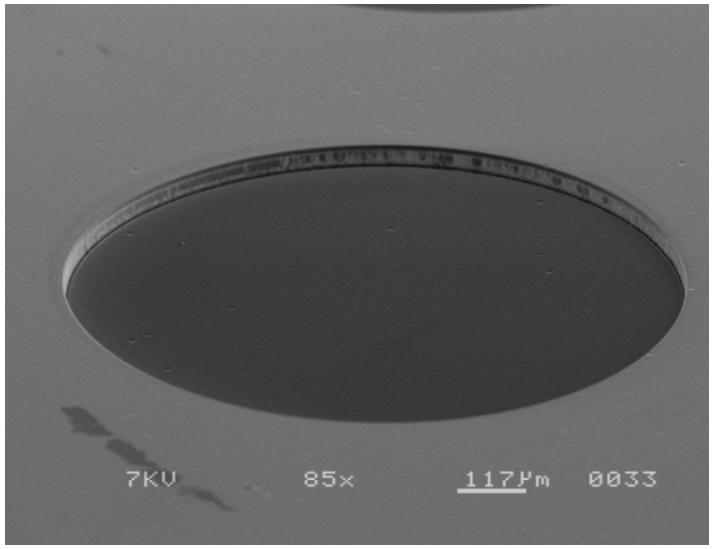
Micromachining methods for SiC:

- **Electrochemical etching**
  - **developed by Kulite, early 1990's**



Backside of SiC diaphragm fabricated by electrochemical etching
60 μm etch depth; 1 mm diam

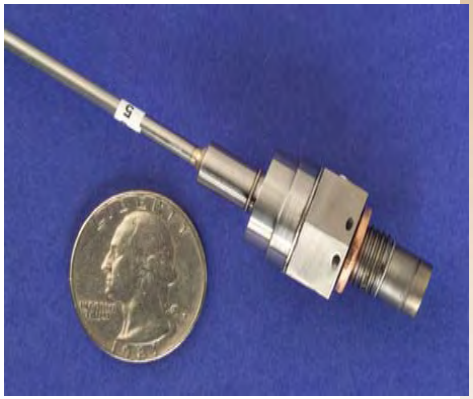
- **Deep reactive ion etching (DRIE)**
  - **developed by GRC, 1999**



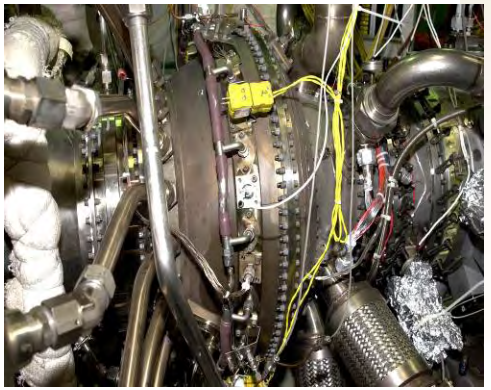
Backside of SiC diaphragm fabricated by DRIE
50 μm etch depth; 1 mm diam

High Temperature SiC Pressure Sensors

- SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR (T > 500 °C, SILICON UNDERGOES PLASTIC DEFORMATION)
- FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS
- WIDE RANGE OF APPLICATIONS
  - AERONAUTIC ENGINE APPLICATIONS
  - AUTOMOTIVE APPLICATIONS
  - MATERIAL PROCESSING
- ENGINE OPERATION DEMONSTRATED AT 500 C
- CAN BE INTEGRATED WITH FLOW VELOCITY AND TEMPERATURE FOR A VENUS HIGH TEMPERATURE WEATHER MONITORING DEVICE

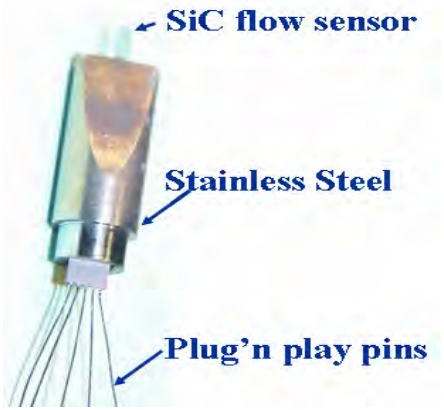


500 °C SiC pressure sensor



Real World Application: Pressure Sensor Installed in Engine Test

SiC High Operating Temp. Probe (HOTProbe): SiC chip to simultaneously measure flow velocity, pressure, and temperature;

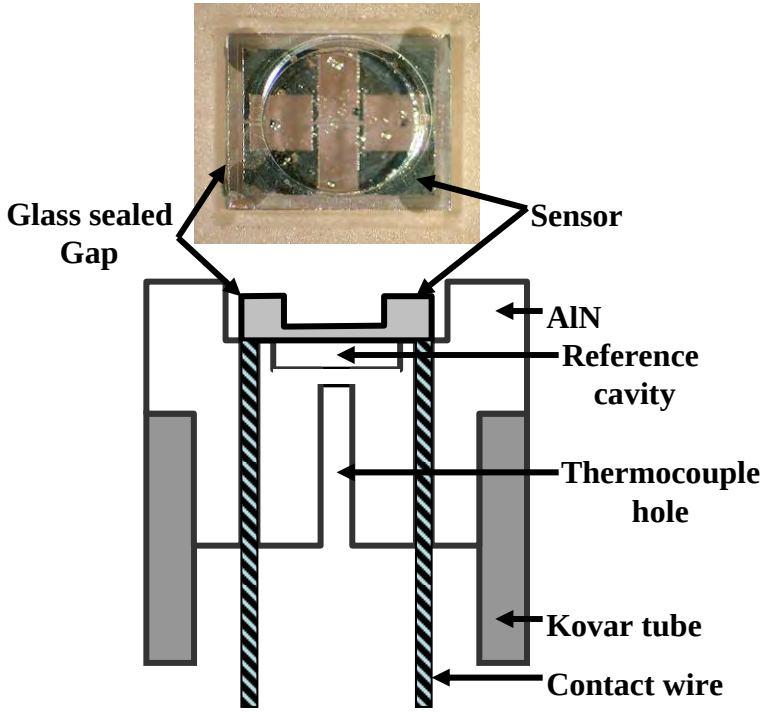


High Temperature SiC Pressure Sensors

Objective:

Develop high temperature (500 to 600 °C) SiC pressure sensors for:

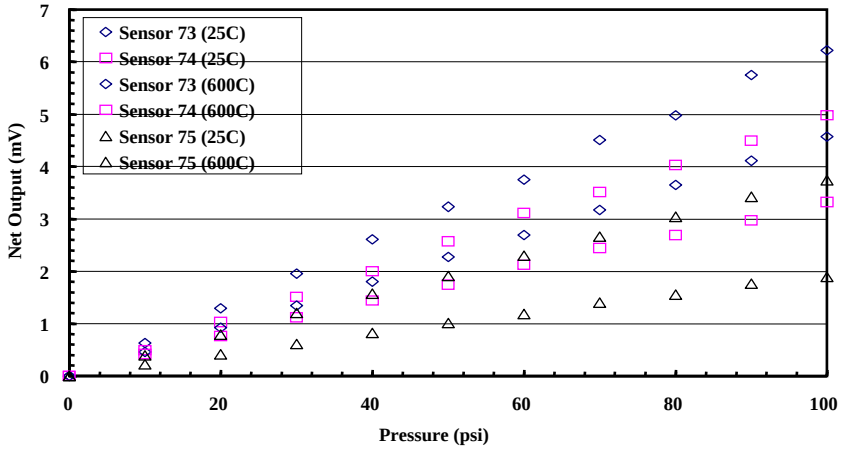
- Engine health monitoring with wireless data transmission
- Active combustion control



MEMS-DCA (Direct Chip Attach) packaged SiC pressure sensor

MEMS-DCA Sensor Attributes:

- Eliminates failures associated with wire bonds at high temperature
- Reduces thermomechanical stress by decoupling sensor from package

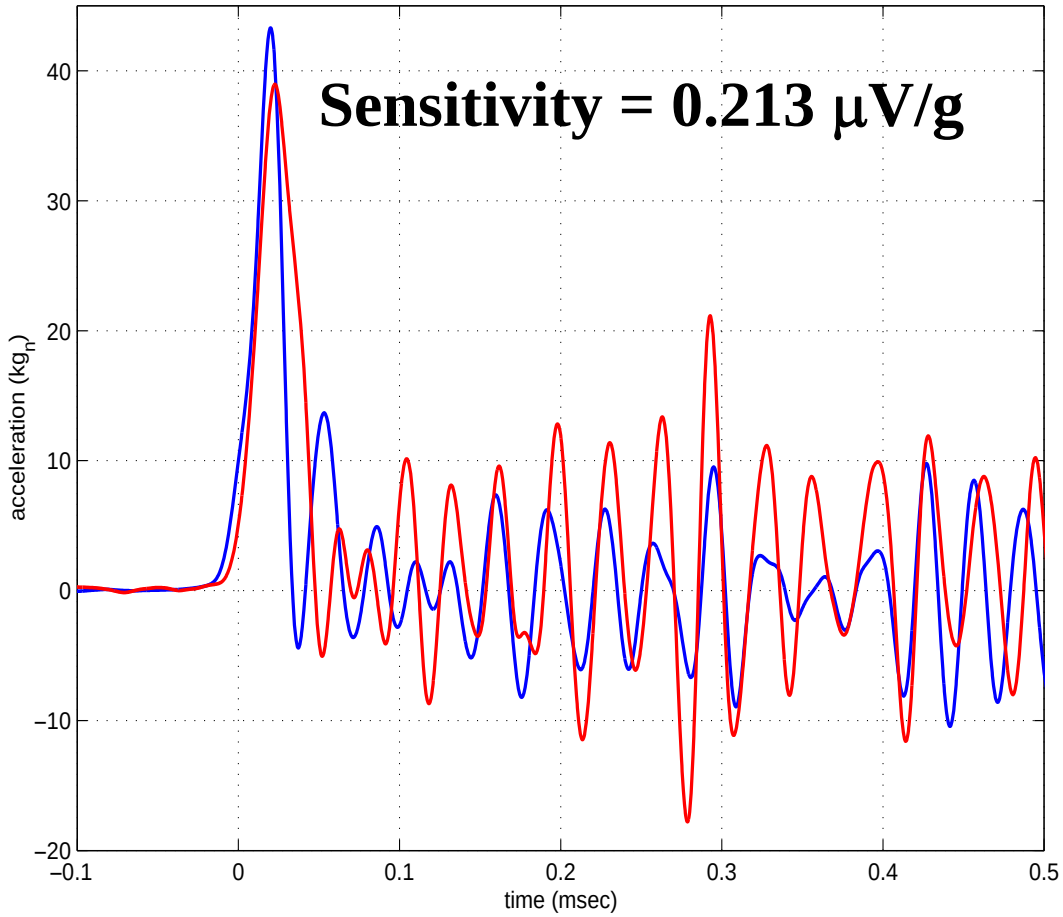


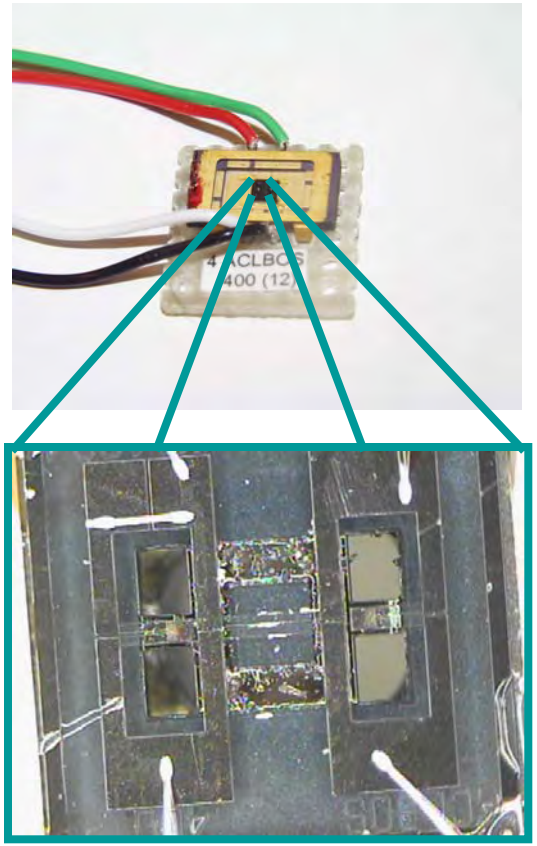
Net output voltage of three SiC pressure sensors tested up to 600 °C

SiC Hi-g Accelerometer

Endevco 7270A-60K

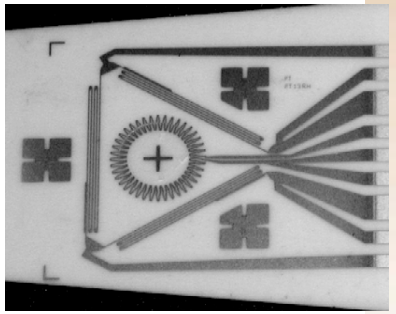
6H-SiC



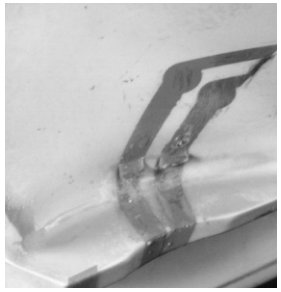


Thin Film Physical Sensors for High Temperature Applications

- **Advantages for temperature, strain, heat flux, flow & pressure measurement:**
  - Negligible mass & minimally intrusive (microns thick)
  - Applicable to all materials including ceramic based materials
  - Minimal structural disturbance
  - Intimate sensor to substrate contact & accurate placement
  - Multiple sensor fabrications, full-field measurement
  - High durability
  - Capable for operation to very high temperatures (> 1000°C)
- **Multifunctional smart sensors being developed**
- **Can Be Used To Measure Venus Surface Conditions as well as Monitor Vehicle Conditions**

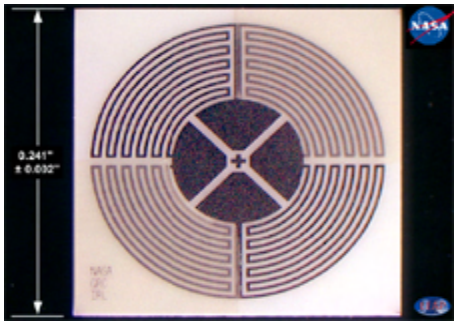


Multifunctional Sensor Array

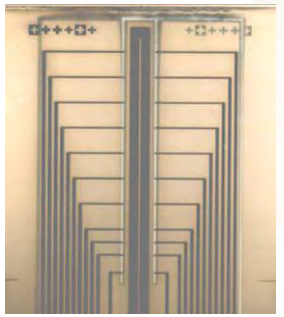


PdCr strain sensor
On Alloy to T=1000°C

Pt- Pt/Rh temperature sensor to T=1200°C



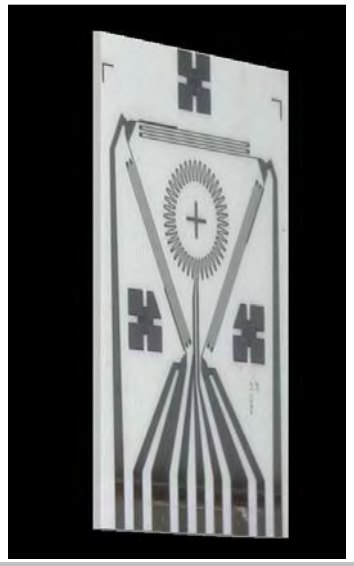
Heat Flux Sensor Array to T=1000°C



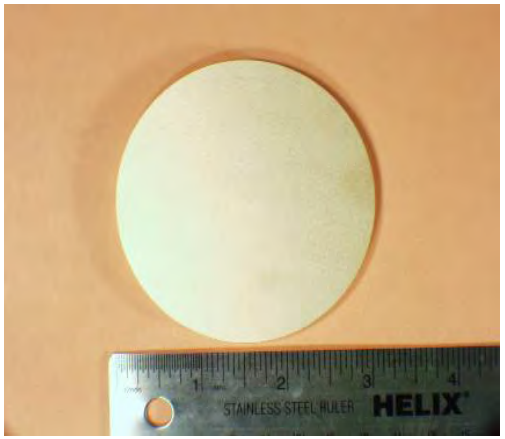
Flow sensor to T=1000°C

Multi-Functional Sensor System/Future Directions

- Temperature, strain, and heat flux with possible flow all one the same microsensor
- Weldable shim designed to simplify sensor mounting
- Materials studied for ceramic TCs – potential to further extend temperature range. (e.g. ITO/ZnO)

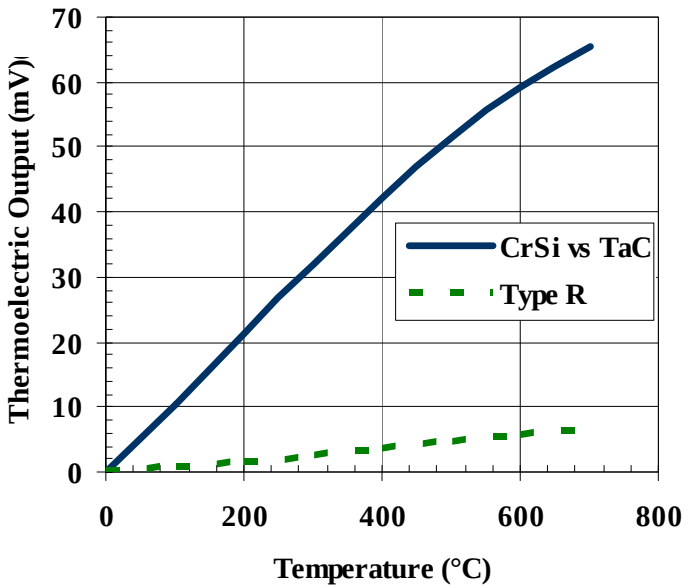


A thin film multifunctional sensor in the geometry of an off-axis rosette.



Material Development for Ceramic Thermocouples

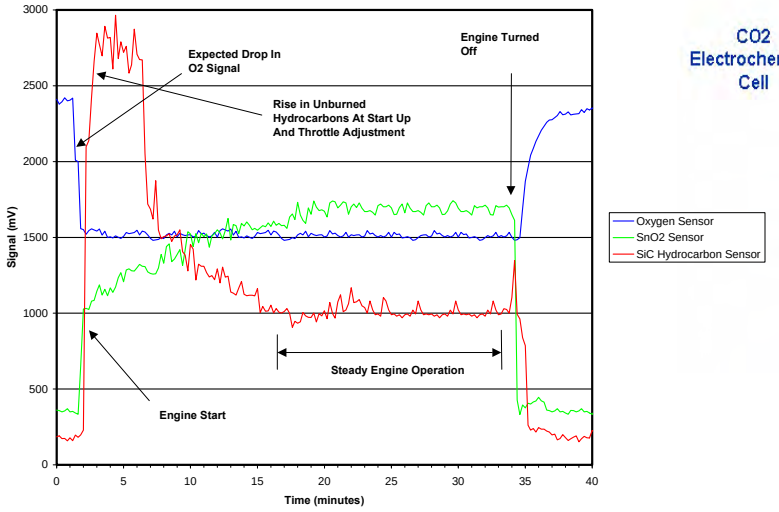
Relative thermoelectric voltage output of the CrSi-TaC thermocouple compared with the standard type R thermocouple.



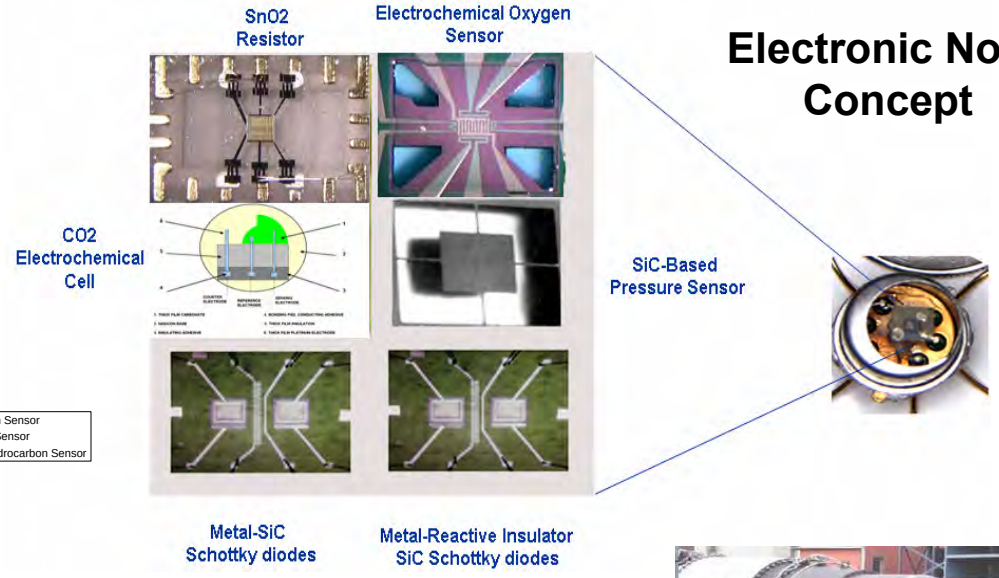
HIGH TEMPERATURE GAS SENSOR ARRAY
HIGH TEMPERATURE ELECTRONIC NOSE

- **High Temperature MEMS Based Gas Sensors Designed for Selective Detection**
- **Multiple Chemical Species Can Be Measured/Sensors Can Be Tailored for the Application**
- **Multiple Species of Interest To Venus Applications Can Be Detected**

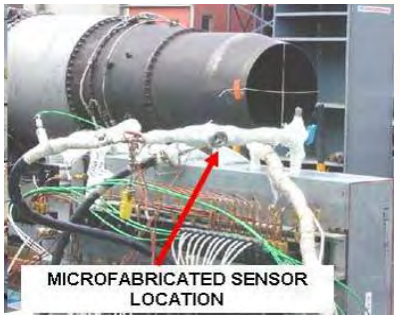
Automotive Engine Sensor Testing



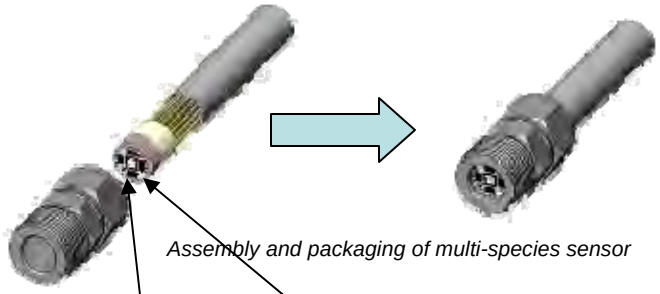
Electronic Nose Concept



Jet Engine Sensor Testing



Multi-Species Gas Sensor Array
Navy Funded Project Description

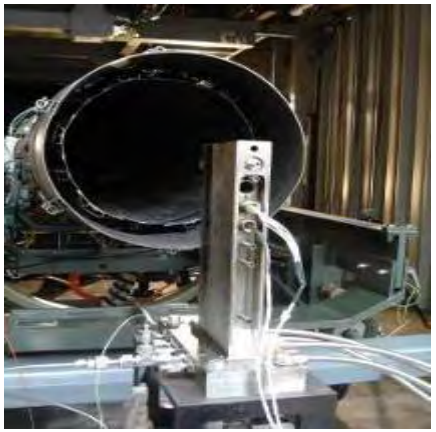


Assembly and packaging of multi-species sensor

Packaged SiC gas sensor

ZrO2 Amperometric Oxygen Sensor

- Develop and validate the MEMS Hot Nose sensor by measuring CO, CO2, NOx, O2, and HC/H2
- Integration into a probe for a range of Gas Turbine emission testing.
- Each sensor will be selective to one of the six chemical species of interest with software algorithms to compensate for any cross-sensitivities
- Flexibility in the interface configuration between the probe and the MEMS gas analysis system for embedded testing in a variety of T&E systems.



MEI Makel Engineering Inc.

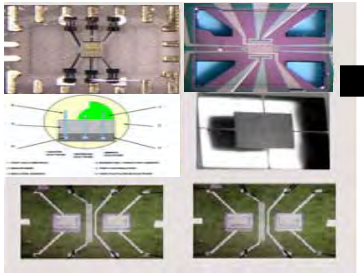
THE OHIO STATE UNIVERSITY

CWRU

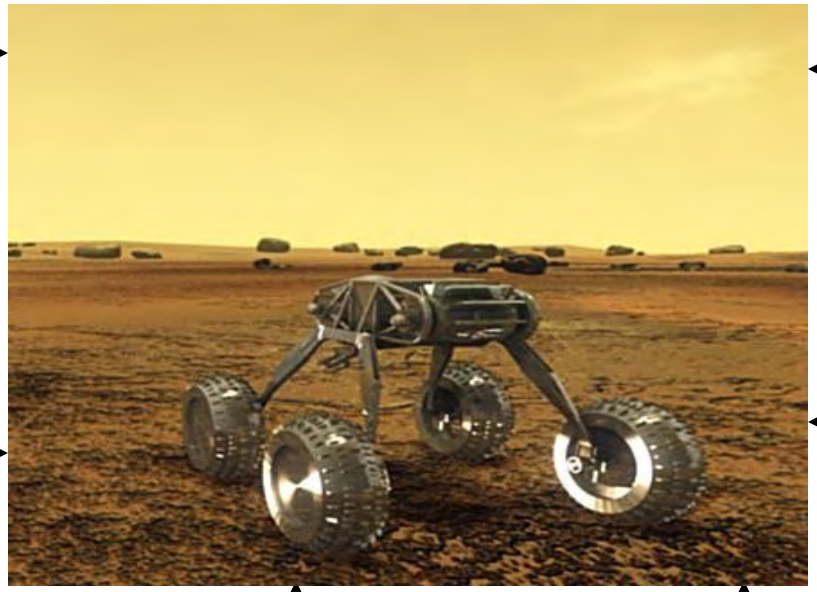
THE BASIC TOOLS EXIST TO ENABLE NEW MISSIONS TAILORING FOR THE APPLICATION IS NECESSARY

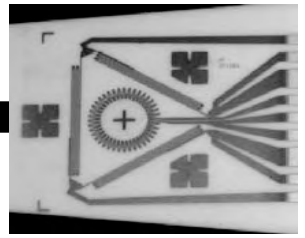
EXAMPLE POSSIBLE MISSION: Venus Integrated Weather Sensor (VIWS) System

Sensor Suite to Monitor Venus Weather Conditions including: Data Processing and Communication, Wind Flow, Seismic, Pressure/Temperature/Heat Flux, Chemical Environment

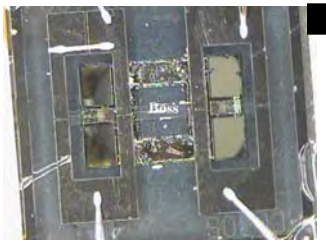


HIGH TEMPERATURE ELECTRONIC NOSE (Chemical Species)





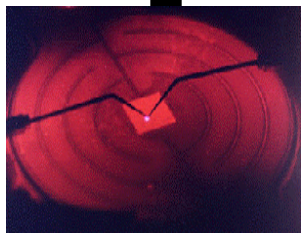
MULTIFUNCTIONAL PHYSICAL SENSOR ARRAY (Temperature, Heat Flux)



Hi-g SiC ACCELEROMETER (Seismic Activities)

HOTProbe (Wind flow, Pressure, Temperature)

PRESSURE SENSOR (Pressure)



SiC ELECTRONICS (Data Processing and Com)

SUMMARY

- HIGH TEMPERATURE SENSORS AND ELECTRONICS NEEDED FOR A RANGE OF SPACE AND AERONAUTIC APPLICATIONS
  - DEVELOPMENT ON-GOING TOWARD SMART SENSOR SYSTEMS FOR ENGINE APPLICATIONS
  - SPECIALIZATION IN MICROSYSTEMS FOR HARSH ENVIRONMENTS
  - HIGH TEMPERATURE, SELF CONTAINED "LICK AND STICK" SYSTEMS
- SIGNIFICANT ADVANCEMENTS HAVE BEEN MADE IN TECHNOLOGY WHICH ENABLES VENUS MISSIONS
- SiC ELECTRONICS OPERATIONAL FOR EXTENDED PERIODS/SCALABLE FOR MORE COMPLEX CIRCUITS
- A RANGE OF HIGH TEMPERATURE SENSORS AVAILABLE
  - THIN FILM PHYSICAL SENSORS
  - HIGH TEMPERATURE PRESSURE SENSORS
  - HIGH TEMPERATURE/HIGH g ACCELEROMETER
  - HIGH TEMPERATURE ELECTRONIC NOSE
- ENHANCED VENUS SCIENCE OBJECTIVES ARE ACHIEVABLE
  - VENUS INTEGRATED WEATHER SENSOR (VIWS) SYSTEM
- AS WITH AERONAUTIC APPLICATONS, TAILORING THE SENSOR SYSTEM FOR THE VENUS APPLICATION IS NECESSARY

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